

*Current*

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**THE WENNER-GREN SYMPOSIUM SERIES**

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**WORKING MEMORY: BEYOND LANGUAGE  
AND SYMBOLISM**

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GUEST EDITORS:

THOMAS WYNN AND FREDERICK L. COOLIDGE

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Beyond Symbolism and Language

Working-Memory Capacity in Cognitive Control

Working Memory and Working Attention

Executive Mechanisms and the Parallel Processing of Meaning

The Phonological Loop

Uses and Abuses of the Enhanced-Working-Memory Hypothesis

Morphological Differences in Parietal Lobes

Making Friends, Making Tools, and Making Symbols

The Emergence of Language

Adhesive Manufacture and Complex Cognition

Working Memory and the Speed of Life

The Evolution of Modern Human Behavior

The Evolution of Modern Cognitive Potential

Modernity and Enhanced Working Memory in the Levant

Australia and the Evolution of Modern Cognition

Working Memory, Neuroanatomy, and Archaeology

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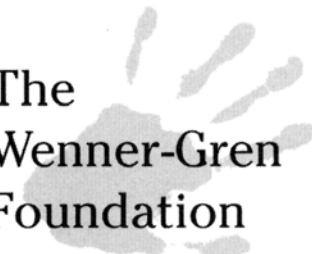
Please send all editorial correspondence to  
Mark Aldenderfer  
School of Social Sciences, Humanities, and Arts  
University of California, Merced  
5200 North Lake Road  
Merced, CA 95343, U.S.A.  
(fax: 209-228-4007; e-mail: [maldenderfer@ucmerced.edu](mailto:maldenderfer@ucmerced.edu))

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# Current Anthropology

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## Working Memory: Beyond Language and Symbolism

*Leslie C. Aiello*

The Wenner-Gren Symposium Series: An Introduction by the President S1

*Leslie C. Aiello*

Working Memory and the Evolution of Modern Thinking: Wenner-Gren Symposium Supplement 1 S3

*Thomas Wynn and Frederick L. Coolidge*

Beyond Symbolism and Language: An Introduction to Supplement 1, *Working Memory* S5

*Randall W. Engle*

Role of Working-Memory Capacity in Cognitive Control S17

*C. Philip Beaman*

Working Memory and Working Attention: What Could Possibly Evolve? S27

*Philip J. Barnard*

From Executive Mechanisms Underlying Perception and Action to the Parallel Processing of Meaning S39

*Francisco Aboitiz, Sebastián Aboitiz, and Ricardo R. García*

The Phonological Loop: A Key Innovation in Human Evolution S55

*Manuel Martín-Loeches*

Uses and Abuses of the Enhanced-Working-Memory Hypothesis in Explaining Modern Thinking S67

*Emiliano Bruner*

Morphological Differences in the Parietal Lobes within the Human Genus: A Neurofunctional Perspective S77

*Matt J. Rossano*

Making Friends, Making Tools, and Making Symbols S89

*Eric Reuland*

Imagination, Planning, and Working Memory: The Emergence of Language S99

*Lyn Wadley*

Compound-Adhesive Manufacture as a Behavioral Proxy for Complex Cognition in the Middle Stone Age S111

<i>April Nowell</i> Working Memory and the Speed of Life	S121
<i>Stanley H. Ambrose</i> Coevolution of Composite-Tool Technology, Constructive Memory, and Language: Implications for the Evolution of Modern Human Behavior	S135
<i>Miriam Noël Haidle</i> Working-Memory Capacity and the Evolution of Modern Cognitive Potential: Implications from Animal and Early Human Tool Use	S149
<i>Anna Belfer-Cohen and Erella Hovers</i> Modernity, Enhanced Working Memory, and the Middle to Upper Paleolithic Record in the Levant	S167
<i>Iain Davidson</i> The Colonization of Australia and Its Adjacent Islands and the Evolution of Modern Cognition	S177
<i>Rex Welshon</i> Working Memory, Neuroanatomy, and Archaeology	S191

# The Wenner-Gren Symposium Series

An Introduction by the President

by Leslie C. Aiello

This special issue of *Current Anthropology* marks the first in a new biannual series of supplements that will publish papers resulting from Wenner-Gren-sponsored symposia. These symposia (originally called Wenner-Gren International Symposia and now simply Wenner-Gren Symposia) are intensive workshop meetings that bring together international scholars for discussion and debate of topical issues in the field.

## Wenner-Gren Symposia and *Current Anthropology*

The first International Symposium, "Anthropology Today," was held in 1952 under the direction of A. L. Kroeber and a steering committee of eight other major figures in the field. It convened 90 anthropologists for a 2-week program to survey and inventory anthropology during the postwar period of rapid disciplinary expansion. The results of this meeting were published in two influential volumes, *Anthropology Today* (Kroeber 1953) and *An Appraisal of Anthropology Today* (Tax 1953). The symposium also led directly to the establishment of *Current Anthropology* as a means for academic communication among international scholars.

Since 1952, the foundation has held more than 170 symposia on topics spanning the breadth of the field. For 2 decades between 1959 and 1980, many Wenner-Gren Symposia were held at the foundation's European headquarters, Burg Wartenstein Castle (Austria; fig. 1). Burg Wartenstein was a gift to the foundation from Axel Wenner-Gren, who was interested in providing a scenic and congenial venue for anthropological discussions involving the widest possible international participation. During this period the foundation hosted more than 2,000 scholars at 86 symposia held during the summer months.

Burg Wartenstein was sold in 1980, and today's symposia are held at a variety of sites in the United States and abroad that provide a similar ambience. To date there have been 55 postcastle symposia and more than a dozen smaller sponsored conferences and workshops hosting an additional 1,300 schol-

ars. The foundation continues to employ the unique symposium model developed at Burg Wartenstein. Precirculated papers are not read at the meetings but form the basis for extended discussions around a table traditionally covered with green baize. Social events and liberal free time provide opportunities for continued conversation in less formal settings. At modern symposia, laptop computers and other electronic devices are banned from the conference table, facilitating an unencumbered meeting atmosphere.

Many books in all areas of anthropology resulted from these meetings; they were published through the foundation's Viking Fund Publications in Anthropology as well as through special arrangement with select houses (such as Aldine Publishers) and various university presses. Most recently, Richard Fox (Wenner-Gren president, 2000–2005) established the Wenner-Gren International Symposium Series, which comprises 12 edited volumes, with Berg Publishers (Oxford, United Kingdom).

The distinct Wenner-Gren format, as well as a broad range of international and interdisciplinary participants, generates the potential for landmark volumes such as *Man's Role in Changing the Face of the Earth* (Thomas 1956), *Courses toward Urban Life* (Braidwood and Willey 1962), *The Biology of Human Adaptability* (Baker and Weiner 1966), *Man the Hunter* (Lee and DeVore 1968), *Primates: Studies in Adaptation and Variability* (Dolhinow 1968), *Law in Culture and Society* (Nader 1969), *After the Australopithecines* (Butzer and Isaac 1975), *Molecular Anthropology* (Goodman and Tashian 1976), *Early Hominids of Africa* (Jolly 1978), *The Great Apes* (Hamburg and McCown 1979), and *Human Ecology in Savanna Environments* (Harris 1980). More recent volumes include *Cloth and Human Experience* (Weiner and Schneider 1989), *The Time of AIDS* (Herdt and Lindenbaum 1992), *Tools, Language and Cognition in Human Evolution* (Gibson and Ingold 1993), *World Anthropologies* (Ribeiro and Escobar 2006), and *Indigenous Experience Today* (Cadena and Starn 2007).

During her tenure as president of the foundation (1986–1999), Sydel Silverman documented the Wenner-Gren Symposia and published a detailed ethnographic study, *The Beast on the Table: Conferencing with Anthropologists* (Silverman 2002), which offers a distinct perspective on this program.

The foundation is aware that academic publishing is chang-

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**Leslie C. Aiello** is President of the Wenner-Gren Foundation for Anthropological Research (470 Park Avenue South, 8th Floor North, New York, New York 10016, U.S.A.).



Figure 1. Burg Wartenstein Castle near Gloggnitz in the Neunkirchen district of Lower Austria, Austria.

ing. We believe that in the future, Wenner-Gren Symposia outcomes will reach a wider audience and have a greater impact in journal format. Publication in *Current Anthropology* (CA) has the added advantage of electronic access and continued availability, as well as distribution through various programs such as CENI (the Chicago Emerging Nations Initiative), HINARI, AGORA, and OARE, which provide free (or low-cost) access in many areas of the developing world.

We believe that in the modern age of electronic publishing, the decision to make Wenner-Gren Symposia available as supplementary issues of CA is in the spirit and tradition of the Wenner-Gren Foundation, together with CA and the symposium program, to bring the results of international anthropological research and debate to the widest possible audience.

## Proposals for Future Symposia

Symposium topics are initiated by the foundation or are selected from submitted proposals on the basis of the importance and timeliness of the topic; the promise of meaningful exchange among scholars representing diverse perspectives, backgrounds, and fields; and the potential for opening up new approaches to significant problems.

Two symposia are held each year, normally in the spring

(March) and in the fall (September). They are usually 1 week in length (including travel) and comprise up to 20 scholars. The foundation provides full administrative and financial support for the meetings. Foundation staff also work closely with the organizers at all stages of symposium development to ensure a successful and intellectually stimulating meeting. Papers from the symposium receive appropriate peer review before publication in CA.

The foundation welcomes proposals for symposia, and there are two deadlines a year, May 1 and November 1. Full information and application materials can be found at <http://www.wennergren.org/programs/>.

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# Working Memory and the Evolution of Modern Thinking

Wenner-Gren Symposium Supplement 1

by Leslie C. Aiello

“Working Memory and the Evolution of Modern Thinking” is the 139th numbered Wenner-Gren Symposium and the 168th symposium in the overall Wenner-Gren symposium series.<sup>1</sup> The symposium was organized by anthropologist Thomas Wynn and psychologist Frederick Coolidge and held March 7–14, 2008, at Fortaleza do Guincho, Cascais, Portugal. Its purpose was to investigate the hypothesis that working-memory capacity evolved over the course of human evolution and that its final enhancement in the recent past enabled the rapid expansion of modern humans at the expense of more archaic hominins.

Working memory, the ability to hold information in attention and process it, has been the focus of considerable research in the cognitive sciences but has received relatively little attention among anthropologists. This symposium brought together cognitive scientists involved in the study of working memory with paleoanthropologists studying human evolution to discuss and debate issues around the evolution of working memory and its manifestation in the human evolutionary record. (Participants are shown in fig. 1.)

Although there was no general agreement on the nature of working memory, there was consensus on the importance of an explicit cognitive theory such as working memory to generate appropriate tests of cognitive development. For example, all agreed on the importance of expanding the archaeological evidence of modern human cognition from, say, the presence of blades or personal ornamentation to features such as hafting, complex sequences of tool production, remotely operated traps, and colonization of oceanic islands.

This symposium builds on earlier Wenner-Gren Symposia that have explored human cognitive and behavioral evolution,

including *Tools, Language and Cognition in Human Evolution* (Gibson and Ingold 1993) and *Roots of Human Sociality: Culture, Cognition and Interaction* (Enfield and Levinson 2006). The foundation also has a long history of symposia on various aspects of human and primate evolution including, among many others, *Social Life of Early Man* (Washburn 1961), *Background to Evolution in Africa* (Bishop and Clark 1967), *Earliest Man and Environments in the Lake Rudolf Basin* (Coppens et al. 1976), and *Phylogeny of the Primates: A Multidisciplinary Approach* (Luckett and Szalay 1975).

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**Leslie C. Aiello** is President of the Wenner-Gren Foundation for Anthropological Research (470 Park Avenue South, 8th Floor North, New York, New York 10016, U.S.A.).

1. The numbering system began with the first symposium held at Burg Wartenstein Castle in 1958 (the “International Symposium on Current Anthropology” organized by Sol Tax). During the castle years only those symposia actually held at the castle were numbered. After the sale of the castle in 1980, the symposia held elsewhere continued the numbered sequence. There were 31 nonnumbered symposia held between 1952 and 1986.



Figure 1. Participants in the “Working Memory and the Evolution of Modern Thinking” symposium. Seated from left: April Nowell, Anna Belfer-Cohen, Alexandra Sumner, Lyn Wadley, Leslie Aiello, Fatima Pinto (Wenner-Gren staff), Miriam Haidle. Standing from left: Francisco Aboitiz, Stanley Ambrose, Rex Welshon, Tom Wynn, Eric Reuland, Matt Rossano, Randall Engle, Fred Coolidge, Iain Davidson, Manuel Martín-Loeches, Philip Barnard. Not pictured: Emiliano Bruner.



# Beyond Symbolism and Language

## An Introduction to Supplement 1, *Working Memory*

by Thomas Wynn and Frederick L. Coolidge

Despite 20 years of concerted attention, paleoanthropology has established little of substance concerning the evolution of the modern mind, if by substance we mean conclusions that would be of interest and use to scholars of human cognition. Part of this failure can be linked to a poverty of appropriate interpretive concepts. There is more to the modern mind than symbolism and language, the two “abilities” most often cited in the paleoanthropological literature. Modern humans have a sophisticated ability to make and execute elaborate plans of action, something known in the cognitive science literature as *executive functions*. Cognitive science has further established that these executive functions are enabled by *working memory*, an interpretive concept introduced by Alan Baddeley in 1974 and subsequently tested by more than 30 years of intensive research. Recently, Coolidge and Wynn have advanced a controversial hypothesis that it was an enhancement of working-memory capacity that powered the final evolution of the modern mind. Wenner-Gren International Symposium 139 met in March 2008 in Cascais, Portugal, to discuss this hypothesis and the evolution of working memory and executive reasoning in general.

Consider the following scenarios:

1. A Kansas farmer planted 25% more acreage in maize despite having had a poor harvest the previous year and despite the marginal condition of his land (in terms of rainfall) for maize production. When asked why he had chosen to do this, he replied that the price of crude oil had risen above \$100 a barrel.

2. Toward the end of the rainy season, a hunter-gatherer in Western Australia sets an intentional bushfire and burns a sizeable tract of land. This results in a second green-up, which attracts the herbivores that are an important component of his diet. A year later, he sets fire to a different tract of land; he does not return to the original tract for more than a decade.

3. Professor Smith has been asked to review a manuscript for a prestigious journal edited by Professor Jones, whom Smith has met but does not know well. The manuscript is by Professor Hernandez, who is a competitor of Smith's. However, Smith also knows that Hernandez is on good terms with Jones and that Jones regularly reviews National Science Foundation proposals on this particular research topic. The research reported in the manuscript is similar to the research done by Smith, who detects flaws in Hernandez's approach.

Instead of recommending rejection, Smith recommends publication with minor revisions.

4. In *Hamlet*, Shakespeare has Hamlet enlist a group of actors to present a play, the plot of which Hamlet has altered, to Gertrude and Claudius. Shakespeare uses their reactions as a means for Hamlet to confirm the account of his father's death given him by his father's ghost.

5. Ms. Jones, an American cook, prepares a Thanksgiving feast for 15 members of her extended family. She prepares a turkey (1 hour preparation time, 7 hours baking, 1 hour “resting”), mashed potatoes (10 minutes preparation, 1 half hour boiling, 10 minutes final preparation), glazed onions (20 minutes), French bean casserole (20 minutes preparation, 1 half hour baking), rolls (10 minutes mixing, 5 minutes kneading, 2 hour rising, 20 minutes shaping, 20 minutes baking), and tossed salad (10 minutes preparation). She times the process so that all of the dishes are ready to serve at the same time, all the while chatting with a sister she has not seen for six months and deflecting suggestions from her mother-in-law.

It is very, very unlikely—impossible, really—that an ape, or a dolphin for that matter, could conceive and execute any of these scenarios. Moreover, language alone would appear insufficient to account for them. There is something else at play, something that involves an ability to construct and carry out elaborate plans of action. It is an ability that is fundamental to human thinking and that underpins much of our success. Cognitive scientists and psychologists use the label

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**Thomas Wynn** is Professor of Anthropology and **Frederick L. Coolidge** is Professor of Psychology at the University of Colorado at Colorado Springs (Colorado Springs, Colorado 80933, U.S.A. [twynn@uccs.edu]).

*executive functions* to refer to these high-level reasoning abilities. They must have evolved during the course of human evolution. But when? And how?

## Paleoanthropology and the Modern Mind

Ever since the publication of *The Human Revolution* (Mellars and Stringer 1989), paleoanthropology has been drawn to (some might say obsessed by) questions concerning the origins of modernity. Hundreds (perhaps even thousands) of books, monographs, and articles have been devoted to the topic. Most focus on the issues of where and when modern anatomy or behavior first emerged, but many also debate how the process played out (e.g., replacement vs. independent origins) and the appropriate methods for recognizing modern behavior. There have been several influential reviews of these issues (Klein 2000; Klein and Edgar 2002; McBrearty and Brooks 2000), including some in *Current Anthropology* (Henshilwood and Marean 2003; Mellars 1989). Unfortunately, there have been fewer well-informed discussions of just what modern behavior entails. To be sure, many arguments embed references to demographic change, cognition, or, more commonly, symbolic culture or language. But these are most often treated as undeveloped suggestions, as when McBrearty and Brooks (2000) cited abstract reasoning and when Mellars (1989) cited syntactical language. Without better development, such “abilities” are just too general to carry much persuasive punch. One result of this naïveté is that little of substance has been established about the evolution of modern cognition, if by substance we mean conclusions that would be of interest to scholars of human cognition. Cognitive scientists cannot go to the paleoanthropological literature to learn much that is serious and useful about cognitive evolution. Yes, spectacular evidence, such as the Chauvet paintings or the beads from Blombos Cave, attracts general scholarly attention because of its inherent wow factor, but to date, paleoanthropologists have not been very good at explaining the behavioral and cognitive implications that their evidence holds for issues outside of the parochial domains of archaeology or human paleontology.

Notable exceptions to this parochial vagueness about the nature of the modern mind have been arguments that cite language as the key to modern thinking (see, e.g., Noble and Davidson 1996). But among the many recent references to “symbolism” or “fully syntactical language,” it is difficult to find treatments that are critical and well developed. It is as if most paleoanthropologists have simply agreed, with little serious thought, that symbolism and language are the abilities that enabled modern thinking. Yes, there is an archaeological record of beads and other products that strike paleoanthropologists as somehow “symbolic,” especially the impressive depictive images from the European Upper Paleolithic. Yet there are still profound methodological problems with the chain of reasoning used by paleoanthropologists to argue for

the presence of symbolism and language from this kind of evidence.

At the 2006 Cradle of Language Conference in Stellenbosch, South Africa (the title is quite telling), linguist Rudolf Botha threw down the gauntlet to paleoanthropologists with an elegant critique of an archaeological argument for language (Botha 2008, 2009). D’Errico and Henshilwood had argued that the 77,000-year-old beads from Blombos Cave in South Africa were evidence for “fully syntactical language” (d’Errico, Henshilwood, and Nilssen 2001; d’Errico et al. 2005). Botha, however, noted that the chain of reasoning from punctured *Nassarius* shells to syntactical language requires three indispensable bridging arguments, each based in the persuasive use of evidence: (1) evidence that the shells were beads, (2) evidence that the beads were symbols, and (3) evidence that the symbols required syntax. Botha concluded that d’Errico and Henshilwood had succeeded only in building the first bridging argument. They produced no compelling argument that the beads must have been symbols or that the symbols required syntax. In other words, the argument that beads are evidence for syntactical language failed. More recently, Henshilwood and Dubreuil (2009) have taken up Botha’s challenge and, using concepts derived from cognitive science, successfully built the second bridge and perhaps threw a line across the third gap.

Botha’s (2008, 2009) critique and Henshilwood and Dubreuil’s (2009) response delineate very clearly a weakness inherent in arguments for the evolution of language, but this weakness applies to almost all arguments for the modern mind. More often than not, paleoanthropologists fail to apply the same level of rigor to every step in the logic of their argument. They focus on the nuts-and-bolts issues of what, where, and when but then fall back on weak assertions when it comes to just what the evidence means. To be persuasive, all of the links in the argument must be explicit and constructed with equal care, but to do this, one must have an understanding of the phenomenon under investigation, and it is here that paleoanthropologists have often been remiss. Just what *is* a modern mind? Simply citing abstract thinking or symbolism will not do. These are not rigorous analytical concepts; they are, in fact, little more than folk categories. We can do much better. Modern cognitive science is replete with well-defined cognitive abilities, many of which can now be tentatively linked to specific neural substrates. Because these abilities have been isolated experimentally and confirmed through a variety of protocols, they have tremendous interpretive power. Cognitive science does, in fact, know something about the modern mind. Unwillingness to engage this literature condemns paleoanthropology to marginality in the study of the human mind. One might counter, as Francesco d’Errico (d’Errico et al. 2003) has done, that archaeology and human paleontology are rich enough to carry the load. But it is precisely this parochial stance that is responsible for the failure of paleoanthropology to have much influence beyond the narrow scope of our own academic journals. When,

in direct response to Botha's challenge, Henshilwood and Dubreuil did turn to cognitive science, they found the concepts they needed to construct a more compelling bridging argument; what had been vague is now explicit.

If paleoanthropology takes a more disciplined look at cognitive science, many commonsense misconceptions would vanish. One such misconception is the notion that the modern mind is somehow one thing and that the transition from archaic to modern occurred via one dramatic reorganization of the brain. To be fair, few would put it so baldly, but many paleoanthropologists treat modernity as a kind of package deal. The most significant accomplishment of evolutionary cognitive archaeology has been the clear documentation that cognitive evolution has been a mosaic. Some modern cognitive abilities evolved a long time ago (e.g., spatial by cognition 500,000 years ago; Wynn 2002), and others evolved more recently. It is almost certainly wrong to claim that the modern mind evolved whole cloth at a single time, but we may be able to trace the evolution of more circumscribed components of modern cognition. One set of these are the executive functions of the frontal lobes and the working-memory capacity that enables them.

## Executive Functions

On September 13, 1848, a responsible, capable, and virile 25-year-old foreman of a railroad construction crew named Phineas Gage accidentally dropped a 13.25-pound iron tamping rod on a dynamite charge. The resulting explosion drove the rod through the left side of Gage's face and out through the top of the frontal portion of his cranium. Remarkably, Gage survived the accident, but he was not the same. His heretofore well-developed business acumen had vanished; he would make plans and change them capriciously. He also lost his usual concern about price when purchasing items. The original contractors who had hired him considered the "change in his mind" so great that they refused to rehire him. Interestingly, other than a new tendency to use profanity, Gage's language abilities were unaffected, and his memory and general intelligence remained intact (Harlow 1868).

In the psychological literature, the quote "no longer Gage" has more often become associated with Phineas's personality changes: his postmorbidity use of profanity as well as depression, irritability, and capriciousness. Clearly, though, it seems that Phineas's most important change was the loss of his once shrewd business acumen and his former ability in "executing all of his plans of operation" (Harlow 1868:340). It must have been these latter abilities that originally made him valuable as a foreman. One of the most prominent neuropsychologists of modern times, Alexander Luria (1966), wrote extensively about these executive functions of the frontal lobes. He noted that patients with frontal lobe damage frequently had their speech, motor abilities, and sensations intact yet their complex psychological activities were tremendously impaired. He observed that they were often unable to carry out complex,

purposeful, and goal-directed actions. Furthermore, he found that they could not accurately evaluate the success or failure of their behaviors, especially in terms of using the information to change their future behavior. Luria found that these patients were unconcerned with their failures and were hesitant, indecisive, and indifferent to the loss of their critical awareness of their own behaviors. Lezak (1982), a contemporary American neuropsychologist, wrote that the executive functions of the frontal lobes were

the heart of all socially useful, personally enhancing, constructive, and creative abilities. . . . Impairment or loss of these functions compromises a person's capacity to maintain an independent, constructively self-serving, and socially productive life no matter how well he can see and hear, walk and talk, and perform tests. (281)

Welsh and Pennington (1988) defined executive functions in a neuropsychological perspective as the ability to maintain an appropriate problem-solving set for the attainment of a future goal. Pennington and Ozonoff (1996) view the domain of executive functions as distinct from cognitive domains such as sensation, perception, language, and long-term memory. Also, they see it as overlapping with such domains as attention, reasoning, and problem solving "but not perfectly" (Pennington and Ozonoff 1996:54). They also add interference control, inhibition, and integration across space and time as other aspects of executive function. Their central view of executive function is a

context-specific action selection, especially in the face of strongly competing, but context-inappropriate, responses. Another central idea is maximal constraint satisfaction in action selection, which requires the integration of constraints from a variety of other domains, such as perception, memory, affect, and motivation. Hence, much complex behavior requires executive function, especially much human social behavior. (Pennington and Ozonoff 1996:54)

The ability to integrate across space and time, or sequential memory function, is, no doubt, another salient feature of the executive functions. Successful planning for goal attainment would require the ability to sequence a series of activities in their proper order. Current neuropsychological assessment of executive functions invariably includes measures of planning, sequential memory, and temporal-order memory (e.g., Lezak 1995). It is also important to note that the frontal lobes have greater interconnectivity to subcortical regions of the brain than do any of the other lobes of the cortex. The frontal lobes have extensive and reciprocal connections to the thalamus, basal ganglia, and limbic system and also posterior portions of the cortex (Bechara et al. 1999; Fuster 1979; Gazzaniga, Ivry, and Mangun 2002; Luria 1973).

On a commonsense level, then, this ability to strategize and plan complex actions sets us apart from even our near relatives and makes a better a priori candidate than language or symbolism for the development that produced the modern mind.

An important component, indeed probably the key cognitive ability enabling executive functions, is working-memory capacity (Kane and Engle 2002).

## Working Memory

*Working memory* refers to a cognitive model elaborated in 1974 by experimental psychologists Alan Baddeley and Graham Hitch that has dominated and stimulated contemporary memory research, particularly over the past 2 decades (Baddeley and Hitch 1974). The working-memory model has also integrated and synthesized research and concepts from other fields such as psychology, neurology, and neuropsychology. Even more important, various psychometric measures of working-memory capacity have been found to be correlated with a variety of critical cognitive abilities, including reading comprehension, vocabulary learning, language comprehension, language acquisition, second-language learning, spelling, storytelling, logical and emotional reasoning, suppression of designated events, certain types of psychopathology, fluid intelligence, and general intelligence. The relationship with fluid intelligence is an important one because fluid intelligence measures one's ability to solve novel problems. It appears less influenced by learning and culture and more influenced by some feral or inherent ability to figure out solutions to problems. Thus, the working-memory model is a natural heuristic for inquiries into the evolution of modern thinking.

The current working-memory model includes an attentional panmodal controller or central executive and two subsystems, the phonological loop and the visuospatial sketch pad. The phonological loop contains two elements, a short-term phonological store of speech and other sounds and an articulatory loop that maintains and rehearses information either vocally or subvocally. The visuospatial sketch pad incorporates the maintenance and integration of visual ("what" information such as objects) and spatial ("where" information such as location in space) elements and a means of refreshing it by rehearsal. A fourth and most recent addition to the model (Baddeley 2001) is the episodic buffer, which serves as a temporary memory system for the central executive. In Baddeley's formulation, it integrates and stores information from the other two subsystems.

At the outset of this discussion, it is important to note some misunderstandings and confusion in the literature regarding the term "working memory." It might be useful to differentiate between working memory *sensu stricto* and working memory *sensu lato*. The meaning of working memory when used in the narrow sense is the ability to maintain and manipulate thoughts over a brief period of time despite interference. These thoughts or ideas are most often verbal (lists of words) or nonverbal (facial recognition tasks). When the term "working memory" is used in the broadest sense, as it is in this paper, it refers to Baddeley's (2001; Baddeley and Hitch 1974) multicomponent cognitive model, which includes the phonological loop, visuospatial sketch pad, episodic

buffer, and central executive. Tasks that measure various aspects of the multicomponent working-memory model are deemed to evaluate working-memory capacity. These tasks are known to share significant common variance, although they each contain important and unique domain-specific variance, depending on the nature of the domain measured (e.g., verbal phonological storage, facial recognition, etc.; Engle and Kane 2004).

## The Central Executive

With some modifications, Baddeley and others (Baddeley and Logie 1999; Miyake and Shah 1999) currently view the central executive as either a unitary system or multiple systems of varying functions, including attention, active inhibition, decision making, planning, sequencing, temporal tagging, and the updating, maintenance, and integration of information from the two subsystems. Some brain function models present working memory as simply one subcomponent of the various functions of the prefrontal cortex (PFC). However, with a raft of new evidence from empirical studies (for a review of contemporary working-memory models and empirical evidence, see Miyake and Shah 1999; Osaka, Logie, and D'Esposito 2007), it is more parsimonious to view Baddeley's working-memory model as having subsumed the traditionally defined aspects of executive functions of the PFC. In most current models, working memory not only serves to focus attention and make decisions but also serves as the chief liaison to long-term memory systems and to language comprehension and production. Indeed, Baddeley (1993) has noted that had he approached these systems from the perspective of attention instead of memory, it might have been equally appropriate to label them "working attention." The central executive also takes control when novel tasks are introduced, and one of its important functions is to override preexisting habits and to inhibit prepotent but task-inappropriate responses. The central executive also takes control when danger threatens and task-relevant decisions must be made.

More recently, Kane and Engle (2002) have also given Baddeley's central executive a neural basis (primarily the PFC) based on a wide variety of evidence, including single-cell firing, brain-imaging, and neuropsychological studies. Through the general framework of individual differences, they proposed *executive attention* as the critical component of working memory and whose chief function is the active maintenance of appropriate stimulus representations relevant to goal attainment in the face of interference-rich contexts. Collette and Van der Linden (2002) have also postulated, based on empirical brain-imaging studies, that the central executive component of working memory recruits not only frontal areas but also parietal areas. They conclude that its operation must be understood as an interaction of a network of cerebral and subcortical regions.

Hazy, Frank, and O'Reilly (2006) have proposed a complex model called PBWM (the prefrontal cortex, basal ganglia

working-memory model) that purports to account for the mechanistic basis of working memory, the central executive, and its executive functions. As its name suggests, they view the PFC as critical in maintaining representations of an individual's perceptions in the broadest sense, dynamically updated and regulated by reinforcement learning systems that themselves are based on chemical neurotransmitters (primarily dopamine) activated by the basal ganglia and the amygdala. They further propose that these learning systems can be modified and thus can learn to control themselves and related brain areas in order to act in a task-appropriate manner.

## Phonological Loop

The phonological loop is intimately involved in language use. Baddeley hypothesized that the phonological loop has two components, a brief sound-based storage that fades within a few seconds and an articulatory processor (Baddeley and Hitch 1974). The latter maintains material in the phonological store by vocal or subvocal rehearsal. Spoken information appears to have automatic and obligatory access to phonological storage, and Baddeley therefore hypothesized that the phonological store evolved principally for the demands and acquisition of language. Baddeley and Logie (1999) also wrote that "the phonological loop might reasonably be considered to form a major bottleneck in the process of spoken language comprehension" (41).

Repetition of sounds held in the phonological store, usually by means of the vocal or subvocal articulatory processor, will relegate those sounds into long-term declarative memory if there is sufficient motivation or emotional salience. A strong motivation to memorize or an elevated emotional meaning (e.g., someone to whom you are attracted has an unusual first name) will increase the likelihood that that sound will be successfully transferred into long-term memory. The process of vocal and subvocal articulation also appears to play an important role in memorizing stimuli in the visuospatial sketch pad, for example, thinking or saying, "Ah, a small blue chair!" The phonological loop processes also help to explain why brain-damaged patients who have lost their ability to repeat sounds vocally can still memorize them. However, those patients who cannot create a sound or speech motor form through the phonological loop cannot memorize new material.

## Visuospatial Sketch Pad

In Baddeley's (2001) current formulation, the visuospatial sketch pad is a temporary store for the maintenance and manipulation of visual and spatial information. In experimental psychology, "visual" information encompasses the appearance of a stimulus, often in the form of relatively simple patterns whose components can be altered in the experimental protocol. "Spatial" information, on the other hand, encompasses the locations of stimuli (Logie 1995). Because both are

components of scenes and the input for both came via visual processing, Baddeley initially lumped them together as being held in the same temporary store. However, it soon became apparent that the visual and spatial components of working memory were separable. In studies of individuals with brain damage, Darling and colleagues (Darling, Della Sala, and Logie 2009) identified individuals who had lost the ability to hold the appearance of stimulus in memory but could remember the location and other individuals who could remember location but not appearance. This double dissociation has been confirmed by experimental protocols on normal individuals (Logie 2003).

Complicating the evidence for this dissociation is the problem of sequential presentation. Typically, the experimental protocol in a visual task presents a visual pattern while the participant performs an interference task, such as generating random numbers (because it is a working-memory task, not a short-term-memory task). This is followed by a delay, which is then followed by the test condition (e.g., same or different). The typical spatial protocol, on the other hand, presents a *sequence* of position changes, again while performing an interference task, with the test condition requiring a repetition of the sequence of locations. Thus, the typical visual task was static, and the spatial task was sequential. Sequential monitoring and processing taps the central executive of working memory more than static presentation, making results difficult to interpret. Perhaps the ability to fraction visual from spatial working memory simply results from the greater participation of the central executive in the sequential tasks. However, Rudkin and colleagues (Rudkin, Pearson, and Logie 2007) have recently conducted experiments that have reduced the role of sequential memory in the spatial tasks and have still been able to separate the visual and spatial components of the visuospatial sketch pad. Neuroimaging studies have been able to identify discrete areas of frontal lobe activation for visual and spatial working-memory tasks, with visual information being processed primarily in the posterior ventral PFC and spatial information primarily in the posterior dorsal PFC. This mimics the dorsal-ventral segregation in the initial processing of spatial and visual information in the parietal and temporal lobes, from which the respective areas of the PFC receive selective inputs. Interestingly, when presented with *simultaneous* appearance/location tasks, individuals present diminished activation in each respective area of the PFC, suggesting a mechanism that directs cell groups to task-relevant aspects of the spatial or visual memory (Sala and Courtney 2007).

The separate visual and spatial components in working memory may have a deep evolutionary history. There is no evidence (that we are aware of) that nonhuman primates can coordinate visual and spatial information. If true, then for nonhuman primates, these would be discrete components of working memory, each competing for maintenance and processing. But humans regularly coordinate visual and spatial information in working memory; indeed, as we have seen,

they are rather difficult to tease apart. Archaeological evidence from stone tools (handaxes, to be precise) suggests that an ability to coordinate visual and spatial information was in place by 1.5 million years ago (Wynn 2002), which in turn suggests that this piece of working memory may in fact be older than the phonological components.

## Episodic Buffer

As noted earlier, Baddeley (see Baddeley and Hitch 1974) initially described the central executive as largely attentional in nature without its own storage capacity but eventually realized that it also must have some way to store information independent of the subsystems (how else could phonological, visuospatial, and long-term memory information be integrated?). He thus proposed the episodic buffer as the storage component of the central executive. He endowed the episodic buffer with the ability to bind and integrate the two subsystems—the phonological loop and the visuospatial sketch pad—and also traces from long-term memory via a multimodal code. By attending to multiple sources of information simultaneously, the central executive is able to create models of the environment that themselves can be manipulated to solve problems and even plan future behaviors and alternative strategies so that if a plan fails, another may be chosen or generated.

Baddeley's (2000) concept of an episodic buffer coincides with another cognitive model, episodic memory. An episodic memory is a coherent, storylike reminiscence for an event, often associated with a specific time and place and a feeling signature. Episodic memory is sometimes labeled "personal memory" or "autobiographical memory." A reminiscence, of course, will include specific knowledge and details (known as semantic memory), but its recall and subjective experience will be psychologically and neurologically different from the recall of the semantic components alone (Tulving 2002). Tulving (2002) has proposed that the ability to simulate and contemplate future scenarios has been the driving force in the evolution of episodic memory. He proposed the term "autonoesis" to refer to the ability, unique to humans, to form a special kind of consciousness in which individuals become aware of the subjective time in which past events happened. It is also this ability that allows humans to travel mentally in time. He also offered one other provocative speculation on the nature of episodic memories (Tulving 2002). Mental time travel, by way of episodic processes, allows awareness not only of the past but also of what may happen in the future. "This awareness allows autothetic creatures to reflect on, worry about, and make plans for their own and their progeny's future in a way that those without this capability possibly could not. *Homo sapiens*, taking full advantage of its awareness of its continued existence in time, has transformed the natural world into one of culture and civilization that our distant ancestors, let alone members of other species, possibly could not imagine" (Tulving 2002:20).

Baddeley (2000, 2001) also proposed that greater working memory capacity would allow for the reflection and comparison of multiple past experiences. This might allow an individual to actively choose a future action or create an alternative action rather than simply choose the highest path of probable success. Although an individual would still be better off (compared with one without benefit of past experience) choosing alternatives simply based on the past (an example of an inflexible anticipatory process), Baddeley proposed that greater working-memory capacity would allow for the formulation of mental models more likely to be successful as future behaviors. Shepard (1997) postulated that natural selection favored a perceptual and representational system able to provide implicit knowledge (long-term memory) of the pervasive and enduring properties of the environment and that natural selection also favored a heightened degree of voluntary access to this representational system (created by working memory). This access, he proposed, facilitated the accurate mental simulation of varying actions, allowing the evaluation of the success or failure of these actions without taking a physical risk. Shepard thought that the mere accumulation of facts would not result in advances in scientific human knowledge; these require "thought experiments." He also postulated that every real experiment might have been preceded by thought experiments that increased the probability of the success of the real experiment.

## Heritability of Working Memory

No complex human behavior is without some genetic influence (Turkheimer 2000), and it is clear that the bulk of modern human nature and behavior has evolved via natural selection on genetic mutations over millions of years. There is solid empirical evidence that working memory, its executive functions, and its subsystems have a strong genetic basis. In the first study of its kind, Coolidge, Thede, and Young (2000), in an analysis of child and adolescent twins as rated by their parents, found that a core of executive functions, consisting of planning, organizing, and goal attainment, was highly heritable (77%) and due to an additive (polygenic) genetic influence. Ando, Ono, and Wright (2002) also found a strong additive genetic influence (43%–49%) on working-memory storage and executive functions in both phonological and visuospatial tasks. Rijdsdijk, Vernon, and Boomsma (2002) found a 61% additive heritability (with an 80% confidence interval of 52%–67%) in young adult Dutch twin pairs on a measure of phonological storage capacity. Hansell et al. (2001) found a strong heritability for a physiological measure of the visuospatial sketch pad.

## Enhanced Working Memory

Working-memory capacity undoubtedly evolved over the course of primate and hominin evolution. The nature of this capacity has something to do with attention to task-relevant

stimuli and the ability to maintain this information in active memory. Its nature probably also includes an equally important ability to maintain these relevant memories in the presence of external interference (irrelevant stimuli) and internal interference (overriding inappropriate natural responses or prepotent responses). We have argued that at some point in the not too distant past, an additive genetic mutation or epigenetic event occurred that enhanced working-memory capacity in the direct ancestors of modern *Homo sapiens* (Coolidge and Wynn 2001, 2005, 2009; Wynn and Coolidge 2003, 2004). We were not the first to propose a neural mutation as the basis for modern thinking (Klein and Edgar 2002; Mithen 1996), although none of our predecessors in this regard specified the nature of the mutation or its specific cognitive effects. We were also not the first to propose that working-memory capacity may somehow underlie modern cognition (Russell 1996).

## On the Nature of Enhanced Working Memory

The genetic or epigenetic event could have enhanced general nondomain-specific working-memory capacity, or alternatively, it might have affected one of the components of the central executive's attendant functions. The difficulty with investigating the first alternative is that measures of working-memory capacity must always be operationalized within a specific context, for example, verbal, visual, or spatial. Thus, measures of working-memory capacity can only hint at the nature of nondomain-specific working-memory capacity, and thus, they are biased by the nature of the measurement.

With regard to the second alternative, an enhancement of one of working memory's components, there are as many candidates as there are components in the model, but a few stand out. For example, the inhibitory function of the central executive might be critical for the evolution of modern thinking because the ability to inhibit prepotent but task-inappropriate interference is critical to the attainment of goals. It is also possible that the heritable event enhancing working memory could have affected one of the two main subsystems. A prime candidate here is phonological storage capacity. It is especially provocative that phonological storage capacity is significantly related to general intelligence and fluid intelligence, although to a lesser extent than some other measures of working-memory capacity. Adults who have greater phonological storage capacity have also been found to do better on verbal tests of intelligence and score higher on measures of verbal fluency; they also do better on retroactive and proactive interference tasks (Kane and Engle 2002). In children who are matched on nonverbal intelligence measures, those with greater phonological storage capacity had a larger vocabulary, produced longer utterances, and demonstrated a greater range of syntactic construction (Adams and Gathercole 2000). Furthermore, some linguists have touted recursion as the key to modern language (Hauser, Chomsky, and Fitch

2002; Reuland 2005). Recursion is the grammatical rule that produces certain kinds of embedding or hierarchical sentence construction, but it requires adequate phonological storage capacity for its execution. We cannot practically embed phrases forever; we would simply lose track of the relationships. Aboitiz et al. (2006) have noted that phonological storage capacity allows multiple items to be combinatorially manipulated, allowing for innovation and creativity. Thus, expanded phonological storage capacity may have allowed the speaker to "hold in mind" a greater number of options and, as such, may have given the speaker a greater range of behavioral flexibility and even creativity.

## The Visuospatial Sketch Pad and the Episodic Buffer

How could the episodic buffer be relevant to our concept of enhanced working memory? There is a strong adaptive value in the ability to simulate the future, with potential consequences for innovation and creativity. Tulving (2002) proposed that the ability to simulate and contemplate future scenarios was the driving force in the evolution of episodic memory. Through the recall of episodic memories, humans become mentally aware that time is subjective, and by way of recall of the past and anticipation of the future, they can travel through time. Tulving used the term "autonoesis" to refer to the ability, unique to humans, of a special kind of consciousness that allows individuals to become aware of the subjective time in which past events have happened and in which future events might occur or be anticipated to occur. As noted previously, this anticipation and simulation of future events has been labeled "constructive episodic simulation." This simulation allows the creation of various future events, often drawn on the experience of past events, and allows them to be flexibly rearranged in order to simulate the future options.

## The Archaeology of Executive Functions and Enhanced Working Memory

In our previous work, we concluded that the archaeological record argues for a relatively late enhancement of working-memory capacity. The challenge, of course, lay in identifying archaeological patterns that were reliable indicators of modern working-memory capacity. The patterns we settled on—managed foraging systems that required response inhibition and planning over months or years, facilities that indicated long-range temporal planning, reliable systems of technical gear, and devices designed to ease the load on working-memory capacity itself—all present a shallow time depth in the prehistoric record. There are several ways to interpret this result: (1) reject it on the questionable grounds that absence of evidence is not evidence of absence, (2) conclude that the heritable component of enhanced working memory occurred as long ago as the earliest *Homo sapiens* but that expression in

the archaeological record was delayed by factors of population structure or the ratchet effect of culture change, or (3) accept the result as accurate (Coolidge and Wynn 2005; Wynn and Coolidge 2007).

## Methodological Issues

One goal of the Wenner-Gren symposium on the evolution of working memory was to shift archaeological evidence from the wings to center stage in the study of cognitive evolution. Of the various methods deployed to investigate neurocognitive evolution, archaeology is the only one that studies the actions of real actors in the past. Cognitive archaeology is built on the premise that ancient minds structured the actions of these prehistoric actors and that the material traces of these actions preserve something of the minds themselves. The challenge is methodological: how does one build a persuasive argument about cognition from the material traces of the archaeological record?

For a cognitive archaeological argument to be persuasive, it must have cognitive validity as well as archaeological credibility. In practice, this requires three components.

1. The cognitive ability under investigation must be one recognized or defined by cognitive science. Commonsense categories such as “abstract” or “complex” either have no defined cognitive reality or are too vague to underpin the next two components. To be sure, the cognitive science literature is immense and diverse, and, much like anthropology and evolutionary science, there are many controversies and factions. One cannot simply dip into the literature on human cognition and withdraw an appropriate, usable model; one must have some familiarity with the intellectual context in which it developed and in which it is used. But the payoff—well-defined, experimentally justified descriptions of components of the modern mind—is worth the effort.

2. The cognitive ability under investigation must in fact be required for the activities reconstructed from the archaeological traces. This is the key methodological step. Cognitive theories and experiments rarely address the kinds of activities that archaeologists reconstruct from their data. Indeed, some psychologists refer to such real-world behavior as “feral cognition” and strive to incorporate it into general discussions of the implications of their research. Application of theory to feral cognition and to archaeologically reconstructed activities requires building sound bridging arguments, to use Botha’s (2008) apt phrase. It is here that the value of explicit cognitive models becomes apparent. With such theories, it is possible to extrapolate from experimentally isolated abilities to real-world activities that would require them.

3. The archaeological traces must in fact have required the reconstructed activities. This is the essential archaeological piece to an argument, and it is a step required for almost any archaeologically based reasoning. One of the major challenges here is equifinality, an underappreciated pitfall of archaeological interpretation. Often, many activities can produce

identical or very similar archaeological signatures. One must be confident in the link between archaeological signature and reconstructed activity.

A strict standard of parsimony applies to components 2 and 3. If the archaeological traces could have been generated by simpler actions, or if the actions could have been organized by a simpler cognitive system, then the simpler explanation must be favored. This risks underestimating ability, but there is no other sound way to proceed. Unwarranted adherence to the dictum “absence of evidence is not evidence of absence” underpins too many weak evolutionary arguments.

Archaeological credibility is no different for cognitive archaeology than it is for any other archaeological interpretation. The evidence must have been acquired by sound field and analytical techniques, and it must be reliably situated in time and space. These requirements are easily stated but not so easily met. Indeed, one could argue that the preponderance of time, energy, and resources in any archaeological research is devoted to these nuts-and-bolts issues. But this does not in turn mean that archaeological credibility is more important than cognitive validity in the structure of a cognitive interpretation. Both are equally necessary.

## Participants in the Symposium

It was important for the success of the symposium that we invite cognitive scientists who were active in research related to executive functions and working memory but who were also friendly to the possibility of an evolutionary approach. These participants and their research interests are given below.

**Francisco Aboitiz** is a neurologist interested in the neural basis of working memory in general and the phonological loop in particular (e.g., Aboitiz et al. 2006).

**Philip J. Barnard** is a cognitive scientist with a 30-year interest in information-processing systems. He has developed a sophisticated information-based model of cognitive control mechanisms that he has already begun to apply to the evolutionary record (e.g., Barnard et al. 2007).

**C. Philip Beaman** is a neuropsychologist who has written on working memory and has developed an alternative model of executive reasoning that emphasizes hierarchical organization. He is skeptical of the potential of cognitive archaeology and has already written a criticism of the working-memory hypothesis of Coolidge and Wynn (Beaman 2007). Unfortunately, last-minute personal concerns prevented his attendance in Cascais, but we include his paper here.

**Randall W. Engle** is an experimental psychologist who has been involved in working-memory research for more than 30 years, and he is the author of one of the current leading models for measuring working-memory capacity (Engle and Kane 2004; Kane and Engle 2002).

**Manuel Martín-Loeches** is a neurologist with an interest in working memory. Like Beaman, he has published a criticism of the Coolidge and Wynn hypothesis, but unlike Beaman he has a more sanguine view of the potential of ar-



chaeology to inform about neural process (Martín-Loeches 2006).

**Matt J. Rossano**, though not a working-memory specialist per se, has developed an independent line of psychological research that incorporates paleoanthropological evidence. This initially focused on the evolution of skill and expertise and more recently expanded to include semiotic systems (Rossano 2003, 2007).

We selected paleoanthropologists with an eye to methodological diversity and geographic focus. Because we wanted to emphasize the potential of material culture to document cognitive evolution, we invited archaeologists who had written about cognitive issues; several had been critical of our approach. Their combined expertise encompassed most of the Paleolithic and most of the Old World. These participants and their research interests and accomplishments are given below.

**Stanley H. Ambrose** is the author of a 2001 article in *Science* (Ambrose 2001) that is one of the seminal documents in cognitive archaeology. He has written extensively on the later Paleolithic of Africa and has formulated an influential hypothesis concerning the 70,000-year-old population bottleneck and the subsequent emergence of symbolically mediated social networks.

**Anna Belfer-Cohen** is an authority on the Southwest Asian Paleolithic with extensive experience with Middle and Upper Paleolithic sites and evidence. With Erella Hovers she has written a number of influential articles on the evolution of symbolic behavior (Belfer-Cohen and Hovers 1992; Hovers and Belfer-Cohen 2006).

**Iain Davidson**, with William Noble, is the coauthor of an influential psychologically/archaeologically based model for the evolution of language (Davidson and Noble 1989; Noble and Davidson 1996). He is also an authority on the colonization of the Sahul (Davidson and Noble 1992).

**Miriam Noël Haidle** has developed a technique for describing the organizational complexity of *chaînes opératoires* and has used the technique to contrast the tool use of non-humans, early hominins, and the makers of the 400,000-year-old Schöningen spears (Haidle 2009). The technique has great potential to standardize descriptions of *chaînes opératoires*, allowing more informed cognitive comparisons.

**April Nowell** is a cognitive archaeologist who, along with d'Errico, has written on the evolution of art and symbolism (d'Errico and Nowell 2000; Nowell 2001; Nowell and d'Errico 2007) but has also written important arguments about hand-axes and the Acheulean in general.

**Lyn Wadley** is an authority on the Middle and Later Stone Age of southern Africa. She has written a number of influential articles in cognitive archaeology (Wadley 2003) and recently has been especially active in experimentally based research into the methods and significance of hafting (Wadley, Hodgkiss, and Grant 2009; Wadley, Williamson, and Lombard 2004).

Although our emphasis was to be on the archaeological

evidence for cognition, we also included the paleontological perspective. **Emiliano Bruner** has developed a three-dimensional modeling approach for fossil brain cases, which he has used to document the nonallometric expansion of the *Homo sapiens sapiens* parietal cortex.

Our discussions were enhanced by the active participation of **Leslie Aiello**, current president of the Wenner-Gren Foundation for Anthropological Research.

We did invite a primatologist who withdrew too late in the lead-up to the symposium to replace. And we did invite one linguist. **Eric Reuland** is interested in language evolution, syntax in particular (Reuland 2005, 2009), and is also interested in the relation between grammatical structures and working memory.

Finally, we invited a philosopher and gave him the unenviable task of identifying links and possible ways forward. **Rex Welshon** is an analytical philosopher who has recently completed a book on consciousness (compared with which working memory is child's play!) that includes chapters on evolution (Welshon 2010). In the end, this was arguably our wisest choice.

## Matters Arising from Discussions

The discussions at the symposium ranged across all three of the components necessary for cognitively valid arguments about the evolution of executive functions and other aspects of working memory. Not surprisingly, participants spent a good deal of time examining the nature of working memory itself. Baddeley's initial formulation has been the focus of more than 30 years of research in cognitive psychology, and this long, intense scrutiny has necessitated revisions by Baddeley himself and numerous modifications and elaborations by a generation of researchers. Ironically perhaps, working memory is now much better understood and at the same time less able to account for all of the feats once attributed to it. However, whether in the guise of an updated model or a specific aspect of the model or an altogether different formulation, these cognitive models for higher-level cognitive processes provide powerful concepts that can be applied to the evolutionary record.

Several core questions emerged during the course of the discussions that bear on the possible role of working memory in human evolution.

Is working memory a trait or a state? If it is a trait that one either has or does not have, then sudden "revolutionary" scenarios for its evolution would seem likely. It appears, however, that it is more likely that working memory is a trait that varies in a given population and that individuals have greater or lesser working-memory capacities. If it is a trait that varies in modern populations, then more gradual standard Darwinian scenarios would appear more likely. This does not preclude the possibility that it is also a state, and recent empirical research suggests both characteristics (Schmeichel 2007). One implication of working memory as a state variable is that it

may be quickly depleted by interference such as distractive conditions, emotional decision making, and overuse.

Is working memory inherited or learned? If executive functions are simply a style of thinking that one learns from others, then cultural evolutionary models rather than Darwinian models would need to be invoked. Alternatively, if there is a heritable component, as appears to be the case, then Darwinian processes would need to be taken into account. Again, however, it appears that it is not an either-or proposition. Functions of the central executive (aka executive functions) appear to have a highly heritable component that is instantiated and reinforced (or punished) by one's family and culture.

What is the role of the phonological loop? Is it just one of a number of perceptually based stores accessed by working memory, or does it have some kind of priority, enabling complex linguistic constructions and through them complex thought?

Is working memory a unity or a multiplicity? Is there only a single, nondomain-specific working-memory capacity, or are there several kinds of working memory that one deploys to solve different kinds of problems? The trend in cognitive science has been to fractionate working memory into multiple components. Did they each have a unique and separate evolutionary trajectory, or did the evolution of each affect the evolution of the others? And what is the relationship of their evolution to the evolution of the central executive and its components?

Has the working-memory model run its course? Have students of human evolution come to it at a time when cognitive science itself is looking for alternative formulations that have better explanatory power?

Equally prominent in discussions was the potential (and limitations) of the archaeological record to document executive functions and working memory. Participants made serious attempts to build the arguments necessary to bridge the gap between theory and archaeological evidence. Several of these methodological links provided the grist for much of the discussion.

Miriam Haidle introduced the concept of "problem distance," which describes the number of intervening steps between the initial conception of a problem and its final solution. Several of the participants (e.g., Randall Engle and Philip Barnard) embraced this rubric as a method for linking prehistoric action to working memory and other cognitive models. Multiple intermediate procedural steps often require response inhibition (a critical executive function) and organization over longer spans of time (another executive function).

Several participants (Stanley Ambrose and Lyn Wadley in particular and Philip Beaman *in absentia*) emphasized hierarchical organization, nesting, and systems of goals and sub-goals (goal direction is yet another executive function). Like problem distance, more complex hierarchies have implications for inhibition and control over time (and occasionally over space if distantly located elements must be combined).

Others (e.g., Eric Reuland and Philip Barnard) focused on number and variety of constituent elements of a procedure. Unrestricted combinability and complex sequential organization are well-known components of executive functions. But to work in archaeological analysis, this approach must be able to eliminate the possibility that the sequential organization was the result of well-learned chains of action held in procedural memory.

Still others emphasized the temporal and spatial scope of activities. Stanley Ambrose, Lyn Wadley, and Eric Reuland emphasized the ability to "escape the here and now." This encompasses such long-range activities as colonization, a centerpiece of Iain Davidson's presentation, and maintenance of long-range social networks (emphasized by Matt Rossano and Stanley Ambrose).

Specific archaeological examples also received serious discussion. The temporal scope of the evidence presented at the symposium extended from the Middle Pleistocene through the Late Pleistocene. The geographic range included Africa, Europe, Western Asia, and Australia. Varieties of evidence included colonization, traps, hafting, spears, rock art, innovation, and even the occasional stone tool. Because the focal point of the discussion was an explicit theory of cognition—that of working memory—the usual list of "modern" patterns favored by some archaeologists (blades, large-mammal hunting, personal ornaments, etc.) did not fare particularly well. Instead, less ballyhooed examples received most discussion, attesting to the value of using an explicit cognitive theory to generate appropriate test cases. One example in particular—multicomponent hafted tools—exemplifies the importance of the second requirement for cognitive validity (the posited activity must require the cognitive ability). Does hafting require the cognitive resources of modern executive functions and working memory, or could an alternative cognitive ability—procedural memory, for example—accomplish the same task? If hafting does require modern working memory, then one would need to conclude that this component of modern cognition was in place as long ago as the earliest evidence for hafting, that is, for more than 100,000 years.

## Conclusion

Was the enhancement of working-memory capacity a key component in the evolution of modern human behavior? The general consensus of the participants at this Wenner-Gren International Symposium was that it was. But beyond this facile conclusion, there was much fruitful disagreement about what, exactly, had evolved and how and when it happened, attesting to the potential and the necessity of using established cognitive models in any attempt to document the evolution of the human mind.

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# Role of Working-Memory Capacity in Cognitive Control

by Randall W. Engle

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This paper discusses the psychometric properties important to the measurement of working memory. Domain-specific aspects of working memory, such as the phonological loop and store and the visual and spatial stores, are important to the performance of many real-world tasks and were probably important to the evolution of the modern mind. However, there is little work demonstrating the critical psychometric properties of reliability and validity of measurement of these domain-specific stores. The domain-general aspect of working memory—attention control—on the other hand, has established reliability and validity of measurement. Individual differences in domain-general working-memory capacity have been shown to be important to a wide range of both speech-based and visual/spatial-based tasks. Working-memory capacity appears to be both a trait and a state variable.

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What is working memory? What does it mean when we use the term “working-memory capacity” (WMC)? How do we measure it? Do people differ in WMC in any meaningful way? Is that a trait or a state variable? Is it important in feral cognition? How might it have been important in the evolution of the human mind? What brain and genetic mechanisms might have led to that development? These are all questions I will try to deal with in the following pages with varying levels of confidence in the answers and, in some cases, mere speculation about the answers.

Working memory is a system of domain-specific stores or formats for temporarily representing information along with a domain-general supervisory or executive attention mechanism. The Baddeley and Hitch (1974) model proposed two formats for temporary storage: one based on speech or articulation and the other for representing and maintaining visual/spatial information. More recently, Baddeley (2000) added a multidimensional store allowing binding of information across dimensions. More recent work has shown the need to fractionate these structures into more specialized structures such as one for visual information and another for spatial information (Logie 2003).

However, I have argued that there are as many domain-specific stores as there are different ways of thinking—probably on the order of a few dozen such formats (Engle and Kane 2004). Like Cowan (1995), I conceive of the contents of these “stores” as temporarily activated representations in long-term memory, as links or pointers, as it were, to existing

representations in long-term or secondary memory. These links will decline in strength over time below a threshold of consciousness, but attention to a link will lead to reactivation that can maintain activation above that threshold. Rehearsal is one way in which that is accomplished.

I am confident that each of those domain-specific stores is important in some way to modern cognition and has probably played an important role in the development of the modern mind. The formats proposed in the Baddeley model have been studied extensively, and the phenomena that serve as their basis are large and reliable across experiments, even if they have not demonstrated reliability within the individual. I am also confident that there are individual differences in the practice-developed skill for the various coding formats, and it is also likely that there are differences in the biological mechanisms necessary to perform those functions, both of which would seem to be necessary for a role in evolution. Cognitive psychologists suspect, for instance, that the phonological loop is important, possibly even necessary, the development of language and reading in the individual (Gathercole and Baddeley 1993). However, there has been either far too little work demonstrating the importance of the domain-specific stores in a wide range of real-world cognitive functions or far too little evidence of reliable individual differences in those functions. In fact, while Logie et al. (1996) found strong group effects of two markers of the phonological loop, they found little evidence of reliability of measurement for the effects at the individual level. Thus, we can only speculate about their role in the evolution of the modern mind.

Both visual and spatial working memory were probably important to the development of tool use. Kunde, Müseler, and Heuer (2007), for example, showed that using a lever

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**Randall W. Engle** is Professor at the School of Psychology, Georgia Institute of Technology (654 Cherry Street, Atlanta, Georgia 30332, U.S.A. [randall.Engle@gatech.edu]).

## One simple and two complex span tasks

<u>Simple Span</u>	<u>Reading Span</u> (WMC)	<u>Operation Span</u> (WMC)
B	The tiger leapt to the ridge. B	Is $(3 \times 1) - 1 = 3 ?$ B
N	I'll never forget my days of combat. N	Is $(10 / 2) + 1 = 6 ?$ N
K	Andy was arrested for speeding. K	Is $(8 / 4) - 1 = 1 ?$ K
J	The mirror cast a strange reflection. J	Is $(3 \times 3) + 1 = 12 ?$ J
S	Broccoli is a good source of nutrients. S	Is $(4 \times 3) + 2 = 14 ?$ S

Figure 1. Example of a simple span task, a reading span task, and an operation span task. WMC = working-memory capacity.

requires that the individual be able to manage the image of the hand moving in one direction *and* the other point of the lever moving in an opposite direction at the same time. This development is quite likely independent of language development. It is also likely that both speech-based and visually and spatially based coding formats will require the use of limited-capacity attention control under complex situations involving interference and distraction.

The vast majority of the work on individual differences in working memory has been done in the context of WMC using complex span tasks. I will discuss at some length the measurement of WMC, the observation that many different measures reflect a common construct, psychometric characteristics of reliability and validity of those measures, and the nature of the construct underlying those measures.

### Measurement of WMC

The issue of measurement of WMC became important because of psychometric problems in the measurement of traditional ideas of short-term memory (Crowder 1982). Psychological measures need to satisfy standards of reliability and validity to be of value to either theory or application. Reliability, in psychometric terms, means that there is a consistency of measurement across time and administrations of a task within the same individual. Validity means that the measure consistently predicts performance on some cognitive measure of interest such as comprehension or reasoning. Simple span tasks such as digit span, the historical and prototypical measure of short-term memory, are insufficiently reliable (Dempster and Corkill 1999) and so inconsistently valid that Crowder (1982) signaled “the demise of short-term memory” (291) based partly on the failure of span measures of short-term memory to consistently correlate with important real-world cognition.

Complex span measures modeled after Daneman and Carpenter’s (1980) reading span task have shown themselves to be at least moderately reliable and consistently valid (Engle and Kane 2004) in predicting a huge array of higher-level and real-world cognitive tasks. Figure 1 shows one simple and two complex span tasks using letters as to-be-remembered items.

In the simple span tasks, the subject is presented with one letter at a time and is then asked to recall the letters in correct order. The number of letters will generally vary from two to eight or so, but at least in the way my lab does these tasks, the order of the list length varies randomly so the subject cannot know ahead of time how many letters will be presented until the list presentation has ended. In our version of the reading span task, the subject is given a brief period to read the sentence and to judge whether the sentence makes sense; the letter is then presented for 800 milliseconds before the next sentence is presented. At the end of three to seven such items, the subject is cued to recall the letters by clicking the mouse on letters in a matrix on the screen. In the operation span task, the subject is shown an operation such as “ $(3 \times 1) - 1 =$ ” for a period of time; the next screen shows a digit such as 6, and the subject is to click on the “yes” or “no” box on the screen to indicate whether the digit is the correct answer to the arithmetic operation. The subject is then shown a letter for 800 milliseconds. After three to seven such items, the subject performs recall by clicking with the mouse on a matrix of letters on the screen, as with the reading span task (Unsworth et al. 2005).

Notice that these two tasks have some similarities and some differences. They both involve an easy yet nontrivial verbal task (reading a sentence for meaning in one case and solving a simple arithmetic expression in the other), and that task is iteratively interleaved with a verbal item (in this case a letter) for later recall. However, reading and arithmetic are different

skills, and it would not be surprising if the scores on these two tasks differentially correlated with a higher-level task such as reading comprehension. But that is not what we find. The two tasks account for pretty much the same variance in a wide array of higher-order cognitive tasks, even tasks with a high level of spatial skill such as the Raven's Matrices. The Raven's Progressive Matrices task is arguably the gold standard of general fluid intelligence. It requires the test taker to pick an object or pattern that would best fit in a matrix of other objects or figures. In fact, even complex tasks that have no discernible verbal component seem to measure the same variance in higher-order cognition. Figure 2 shows three different spatial tasks we have used, and they account for quite similar variance to the verbal tasks described above. Each of these three tasks requires the subject to perform some spatial task, such as mentally rotating a letter, deciding whether a figure is symmetrical around a vertical axis, or mentally traveling around a large block letter and deciding whether each subsequent corner was internal or external. That operation was followed by something that the subject was instructed to recall, such as an arrow of a variable length and direction, a highlighted cell in a matrix, or the distance and direction

traveled by a ball. Recall was accomplished by drawing the to-be-recalled objects on paper.

In a structural equation modeling study of the tasks, scores from the complex spatial and complex verbal tasks all loaded on a common construct. As can be seen in figure 3 (*left*), the three verbal and three spatial tasks all had similar loadings on the WMC construct. Further, this construct was strongly associated with a construct for fluid intelligence. Even if the verbal and spatial tasks were forced into a two-construct model, as in the model in figure 3 (*right*), the two were highly correlated at 0.93 (Kane et al. 2004). This and other studies provide support for the idea that the great variety of complex span tasks reflects a unitary construct common to verbal and spatial processing and that the construct is important to a wide range of higher-level tasks, including reading and listening comprehension, complex learning, and reasoning (Engle and Kane 2004; Turner and Engle 1989).

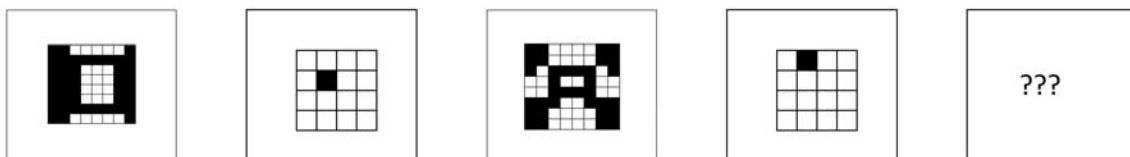
As I mentioned earlier, the two criteria important to any psychological measure are reliability and validity. One way reliability is assessed is to do a split-half correlation of the test. This assesses internal consistency within a session. All of the complex span tasks have split-half reliabilities of 0.7–0.9,

## Spatial WMC Tasks

### Rotation-Arrow Span (set sizes 2 - 5)



### Symmetry-Matrix Span (set sizes 2 - 5)



### Navigation-Ball Span (set sizes 2 - 5)

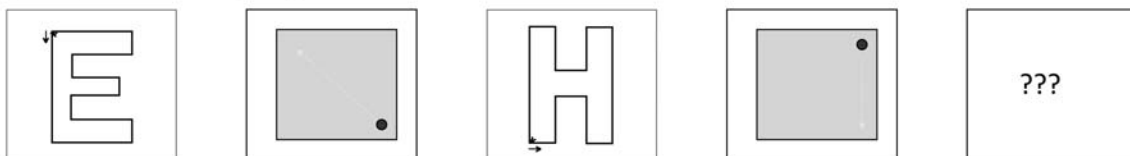


Figure 2. Three different spatial tasks used by Kane et al. (2004).  
WMC = working-memory capacity.

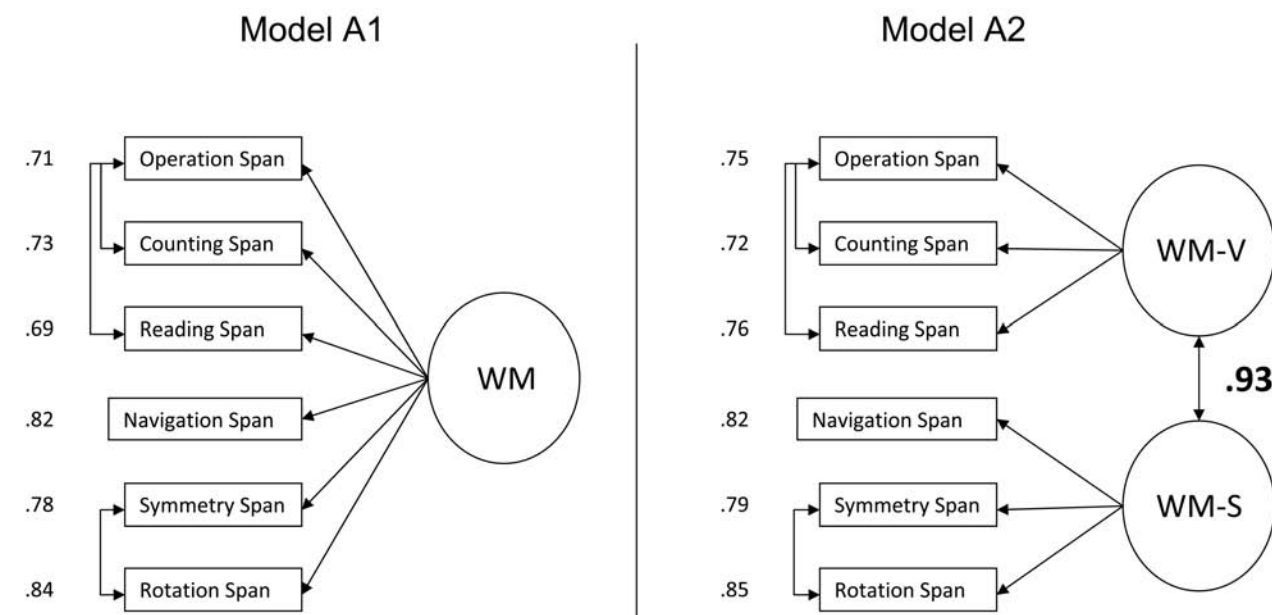


Figure 3. Structural equation model of verbal complex span tasks (operation span, reading span, and counting span) and spatial complex span tasks (navigation span, symmetry span, and rotation span). Adapted from Kane et al. (2004). WM = working memory; WM-V = verbal working memory; WM-S = spatial working memory.

which is quite reasonable. Another way to assess reliability is to administer the same or equivalent forms of the test to the same individuals at two or more different times. Klein and Fiss (1999) tested a group of individuals three times on the operation span task over 9–10 weeks. Scores on the operation span task increased over the administrations because of practice, but the overall corrected reliability was 0.88, suggesting that performance increased evenly across ability levels. Another study of the reliability of the operation span task was conducted by Unsworth et al. (2005). They tested 78 subjects on the automated operation span task and retested them with a mean delay of 13 days. The automated operation span showed a reliability coefficient of 0.83, which is quite high for a lab-based task. Similar studies have not been done with other complex span tasks, but the studies with operation span suggest a high level of reliability over lengthy periods of time and with repeated administrations.

There are multiple ways one can assess validity. Construct validity means that measures thought to reflect the underlying unobservable hypothetical construct should correlate with performance in other tasks for which that construct is deemed important. By this thinking, any of the WMC tasks we have described here, as well as dozens of others that have been used in published reports, should predict performance on any other task in which the hypothesized construct is a crucial mediator of performance. Performance on WMC span tasks has been shown to correlate with a wide range of higher-order cognitive tasks, such as reading and listening comprehension

(Daneman and Carpenter 1983; Daneman and Merikle 1996), language comprehension (King and Just 1991), following oral and spatial directions (Engle, Carullo, and Collins 1991), vocabulary learning from context (Daneman and Green 1986), note taking in class (Kiewra and Benton 1988), writing (Benton et al. 1984), reasoning (Barrouillet 1996; Kyllonen and Christal 1990), hypothesis generation (Dougherty and Hunter 2003), bridge playing (Clarkson-Smith and Hartley 1990), and complex-task learning, such as learning to write programs in a computer language (Kyllonen and Stephens 1990). Low-WMC individuals are less good at blocking intrusive thought than are high-WMC individuals (Brewin and Beaton 2002), which would seem to interact with many different psychopathologies to impair cognition proportionally to the extent that troubling thoughts need to be suppressed.

Many of our studies have used extreme-groups designs to test whether a dependent variable is sensitive to WMC differences. In these studies, we test a broad range of individuals on measures of WMC and use the upper quartile as the high-WMC group and the lower quartile as the low-WMC group. It should be pointed out that the subjects in our broad sample are recruited from college campuses and from large urban centers. Some labs use college students only from large comprehensive universities. Thus, the low-WMC individuals are in no way pathological or nonnormal.

A measure shows discriminant validity to the extent that it does not correlate with measures that the construct should *not* be important to. I will argue below that the construct at



the core of individual differences in measures of WMC is the ability to control attention to keep representations most relevant to the task at hand in active memory or most easily retrievable from inactive memory and that this comes into play most directly under conditions of interference from competing representations. To the extent that this idea has credibility, individuals who are different in WMC should not show differences when cognitive control is minimally required because the task is minimally affected by interference. Kane and Engle (2002) showed that high- and low-WMC individuals showed large differences in the recall of 10-item lists when the lists had been preceded by at least four other lists for recall; however, on the very first list, with no proactive interference to affect recall, high- and low-WMC individuals did not differ in level of recall. Similarly, Unsworth, Schrock, and Engle (2004) showed that in the high-interference anti-saccade task (described in more detail below), low-WMC individuals made many more errors than did high-WMC individuals. However, in the low-interference prosaccade condition, the two groups did not differ in errors.

Another interesting demonstration of the validity of WMC is that individuals measured to be low in WMC appear to have their mind wander when engaged in a task more so than do high-WMC individuals. Michael Kane and his colleagues (Kane et al. 2007a) tested a large number of individuals on a battery of complex span tasks that included the operation span, reading span, and symmetry span. They then provided the subjects with a Palm PDA that beeped a signal randomly eight times each day for 7 days. When the signal occurred, the subjects were to immediately consider whether their mind had wandered from the task they were supposed to be performing at that time. They then entered that information into the PDA and answered a series of other questions. Kane et al. found that low-WMC individuals were more likely than high spans (all students at a large state university) to have their mind wander as the task became more challenging or required more effort or if the subjects were trying hard to concentrate on the task. This finding has great implications for the role of WMC in planning events over the course of the day and in implementing those plans. It would be particularly important to more complex and more difficult plans requiring greater concentration.

There are other measures of WMC than the ones described here, but none of them have the extensive assessment of reliability and validity of the complex span tasks. The N-back task, for example, presents subjects with a series of verbal or pictorial objects and asks them to press a key when an item is identical to the one presented three back in a three-back task or two back in a two-back task. The N-back task has been used almost exclusively in studies using the functional magnetic resonance imaging (fMRI) technology to study brain circuits associated with working memory because it conveniently requires only a two-choice button press to perform the memory task. A recent paper by Kane, Conway, Miura, and Colflesh (Kane et al. 2007b) showed that performance

on a three-back task did correlate with the Raven's score but that scores from a two-back task did not. Kane et al. (2007b) found that the N-back, even three-back, seemed to have little or no overlap with the operation span because they accounted for nearly unique variance in Raven performance. Thus, N-back and the complex span tasks appear to reflect quite different constructs, but there has been little work to determine their similarities and differences. This would appear to be an important field for future work. The vast majority of work on the role of WMC in real-world cognition has been done using complex span tasks, and the vast majority of work on the cognitive neuroscience of working memory has been done using N-back tasks. The fact that these two tasks appear to have little or no overlap in variance seems to present a large conceptual problem to the field.

## Working Memory as a State/Trait Variable

I have presented the work on individual differences in WMC as if it were a trait variable, an abiding characteristic of the individual that remains relatively immutable over time. Of course, it is the trait aspect that is most germane to discussions of the evolution of working memory. But, while there is good evidence to support that approach, it needs to be pointed out here that we need to think of WMC as a state variable as well. In much the same way that psychologists talk about anxiety as reflecting both a trait of the individual and a state that depends on the context, we should think about WMC as both a trait and a state variable. Let me provide some examples.

"Stereotype threat" refers to the fact that individuals perform poorly on a test if a relevant stereotype is associated with performance on that task. For example, women score worse on a mathematics test if they are told before hand that women typically score worse than men on math tests. Schmader and Johns (2003) found that the effect of stereotype threat was mediated by a reduction in WMC. Similarly, Richeson and Shelton (2003) found that it is especially taxing of attention control for a racially biased white individual to interact with a black individual and that the white individual will perform worse on a subsequent task also demanding attention control.

Sleep deprivation and fatigue are also associated with reductions in WMC. A recent study with 10 highly experienced U.S. Air Force pilots measured performance on a sophisticated flight simulator along with a battery of other measures including the operation span every 2 hours while the pilots were kept awake for 35 hours (N. Lopez, F. H. Previc, J. Fischer, C. M. DaLuz, A. J. Workman, W. R. Ercoline, R. H. Evans, N. A. Dillon, R. W. Engle, and R. P. Heitz, unpublished data). Even though the pilots were quite experienced and often flew with little sleep, they made errors in the last half of the 35-hour period, and the errors were highly predicted by performance on the operation span at 0.65. Thus, as fatigue in-

creased, WMC declined, and that was associated with increased errors on the simulator. WMC has also been shown to be affected by stress (Beilock and Carr 2005) and alcohol (Finn 2002). These results do not diminish the importance of WMC as a trait variable; they do, however, point out the difficulty in specifying whether the results for a given individual at a given point in time are driven by state or trait.

## WMC as Attention Control

I have described the considerable work on the psychometric properties of measures of WMC and the huge variety of tasks that seems to depend on that capacity. I will now turn to work on the nature of the construct that is reflected by those tasks. I have argued that the complex span tasks reflect individual differences in the ability to control attention to task-critical representations to keep that information either available in active memory or easily and quickly retrievable from inactive memory. The construct reflects the interface between attention and memory. It is important to strengthening the activation of representations critical to the current task but also important to the dampening or inhibition of representations that would interfere with the task. I will discuss several lines of work supporting the idea that individual differences in WMC reflect differences in attention capability even though the complex span tasks measure the number of items recalled.

One paradigm that has been used to study the regulation

of attention is the dichotic listening procedure in which two different auditory messages are played simultaneously to the two ears and the subjects are instructed to ignore the message coming to one of the ears and to simultaneously repeat the words in the message coming to the attended ear. Subjects are unable to report anything about the words in the ignored message other than some primitive features of the voice of the speaker. However, Moray (1959) found that if he included the subjects' first name among the random words in the ignored ear, about one-third of the subjects reported hearing their name even though they had no idea what the other words were in the ignored message.

If individual differences in WMC reflect differential ability to attend to events important to the current task and to block distracting events, then we should see an interesting difference between high- and low-WMC individuals in the dichotic listening task. If high-WMC individuals are better at blocking distracting information, they should be less likely to hear their own name in the ignored message than should low-span subjects. Conway, Cowan, and Bunting (2001) tested high- and low-WMC individuals on Moray's task, with the subjects' first name inserted by computer into the ignored ear. While only 20% of high-WMC individuals reported hearing their name, 65% of low-WMC individuals heard their name. Presumably, high spans were better at focusing attention on the attended message, which required blocking the distracting message.

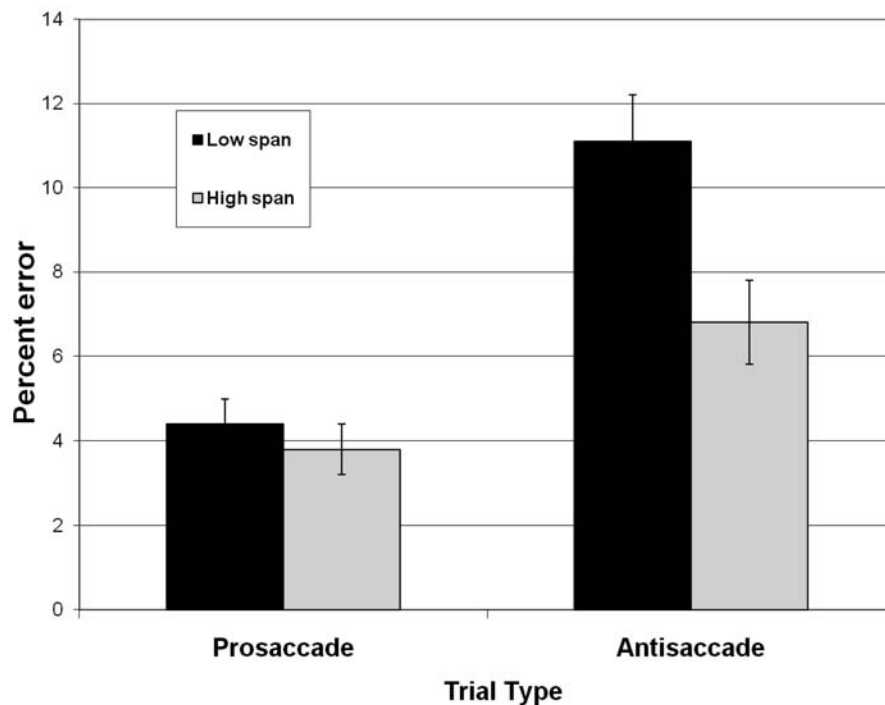


Figure 4. Percent errors for low working-memory capacity (WMC; gray bars) and high-WMC (black bars) subjects in the prosaccade and antisaccade task. Adapted from Unsworth, Schrock, and Engle (2004).

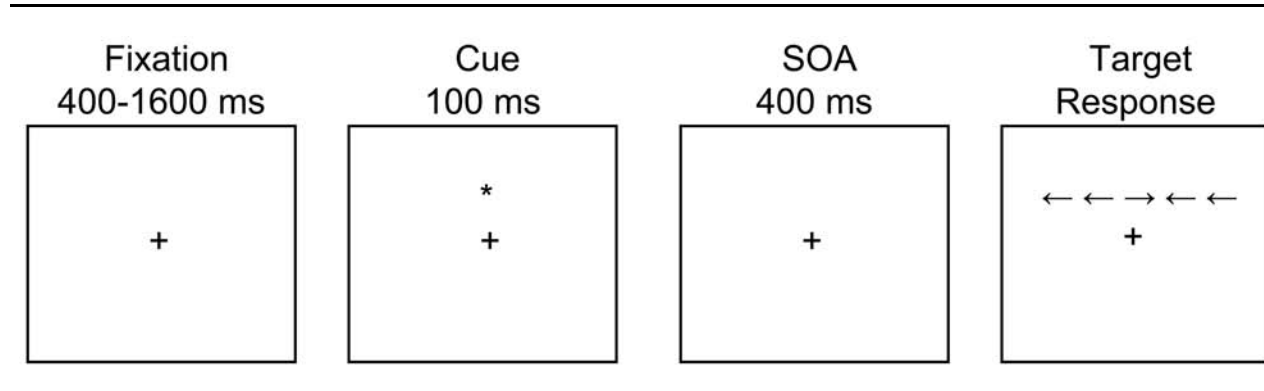


Figure 5. Example of a trial in the attention network task with incompatible flankers surrounding the critical arrow. Adapted from Redick and Engle (2006). SOA = stimulus onset asynchrony.

Another relatively primitive attention task that has been used to study attention differences in WMC is the eye movement task, or the antisaccade task, referred to earlier. In our version of this task (Unsworth, Schrock, and Engle 2004), the subject is seated in front of a computer monitor and must closely monitor a fixation point on the screen. There are two boxes printed on the screen, each approximately  $11^\circ$  from the fixation point. At some point, the fixation figure changes, and soon thereafter one of the boxes flickers. An eye tracker is used to monitor fixation and saccades. There are two conditions in the experiment. In the prosaccade condition, as soon as the box flickers, the subject is to move his or her gaze to the flickering box. In the antisaccade condition, the subject is to immediately move his or her gaze to the non-flickering box. This is an elegantly simple task but is devilishly difficult. Millions of years of evolution have prepared us to immediately move our eyes toward a flickering stimulus. Flicker affords movement, and things that move possibly can eat you—or you can eat them. Either way, detection of movement is vitally important. The experimenter is asking the subject to go against this behavior that is strongly predisposed in virtually all animals and to make the first eye movement in the opposite direction. Even a slight glimpse toward the flickering box is considered an error. However, as can be seen in figure 4, even though high- and low-WMC subjects did not differ on the prosaccade task, low-WMC individuals made many more erroneous saccades on the antisaccade version of the task, meaning that they were much more likely to have their attention captured by the flickering box than were the high-WMC individuals. Notice how dissimilar this task is from the complex span tasks we use to measure WMC. Subjects were chosen on the basis of a task in which they recalled sets of letters or words interleaved with calculating a simple arithmetic string or reading a simple sentence. However, the WMC tasks predicted the number of errors in the antisaccade task involving no verbal or complex spatial processing.

Another approach to studying differences in attention is the attention network task (ANT) developed by Michael Pos-

ner and his colleagues (Fan et al. 2002). This task requires subjects to look at an arrow on a computer screen and press one of two buttons to indicate the direction the arrow is pointing. The task manipulates the types of cues the subject receives before the critical arrow occurs and the nature of the arrows surrounding the critical arrow, and it tests for three different aspects of attention—alerting, orienting, and executive attention—reflecting the ability to resist attention capture by the environment and attend to a task-critical event. An example from an incompatible trial for the executive attention network is shown in figure 5. The subject on this trial is to press a key indicating the direction the center arrow in the fourth panel is pointing. To the extent that attention is captured by the arrows flanking the critical arrow, performance will be slowed, and more errors will occur. Individuals who can effectively block the attention response to the flankers will do better on this task, and that is the prediction of our theory about WMC and attention control. Redick and Engle (2006) tested high- and low-WMC individuals on the ANT. We predicted high/low differences on the executive attention task but were unclear whether to expect differences on the other two aspects of attention. We found that the two groups did *not* differ on alerting or orienting. However, as we expected, low-WMC individuals performed much more poorly on the test of executive attention than did high-WMC individuals. Also, notice that the results of this experiment would not be predicted by any view of capacity limits based on a finite number of objects, such as  $7 \pm 2$  (Miller 1956) or  $4 \pm 1$  (Cowan 2001); in fact, it is not clear why one would even do the study based on that view. However, if one believes that the construct underlying WMC is the ability to regulate and control attention, the study makes perfect sense.

### Psychological Mechanisms Responsible for WMC Differences

I have argued that individual differences are, at base, a result of differences in ability to effectively select representations

that are relevant to the task at hand and to deselect, inhibit, or suppress competing representations. Clearly, low-WMC subjects are very different from high-WMC subjects on very low-level attention tasks such as antisaccade and the ANT. However, can we connect the dots between the complex span tasks and attention control? How do differences in attention control lead to differences in the complex span tasks? First, we need to establish whether people who do well on complex span tasks do well because they maintain more information in active memory or because they are better at constantly moving information from inactive memory back into active memory.

Nash Unsworth and I (Unsworth and Engle 2007a, 2007b) have proposed that complex span tasks work because they require a constant updating of active memory. Think about the operation span task in which the subject is presented with an operation string and then a letter to store for later recall, then another operation string, and then another letter to be stored for later recall. When attention is required to solve the second operation, the subject must allow the representation of the first letter (or all the earlier letters in the emerging list) to decay below the threshold of consciousness. Then, after the operation is solved, the emerging list must be retrieved. If this is the very first list in the task, then the retrieval is pretty simple because there is no interference from previously presented letters. However, if the list is not the first list, then retrieval requires searching among a set of recently active but now inactive (i.e., below-threshold) representations. We have argued that low-WMC subjects are more vulnerable to the effects of interference; thus, during the retrieval phase, they would have to search among a larger set of items—the items from the emerging list *and* the items from the previous list. High-WMC individuals are better able to inhibit or block the activation of the items from the previous lists; thus, they must search among a smaller set of items and are more likely to find and retrieve the new items from the emerging list. One advantage of our executive attention theory is that it is flexible enough to allow high-WMC individuals to use their capability in a number of different ways, depending on what is called for by successful performance on the task at hand.

## Brain and Genetic Mechanisms Responsible for WMC Differences

For working memory and WMC differences to play any role in evolution, they must, of course, have a heritable base. We have argued that individual differences in WMC correspond to the dopaminergic system, specifically, differences in circuitry associated with the prefrontal cortex and the anterior cingulate (Kane and Engle 2002). Studies using fMRI point to these structures as important to individual differences, particularly under the effects of proactive interference (Gray, Chabris, and Braver 2003). Further, the relationship between dopamine and WMC appears to be a nonlinear one. Kimberg, D'Esposito, and Farah (1997) found that administration of a

dopamine agonist, such as bromocriptine, led to enhanced working-memory performance for low-WMC individuals but hurt performance for high-WMC individuals.

Several alleles have been proposed to account for individual differences of the type discussed here. Unfortunately, the empirical research has tended to be unfocused in the nature of the working-memory tasks or has focused on tasks, such as the N-back task or the Wisconsin Card Sort Task, where the reliability and validity concerns about the tasks make conclusions difficult. For example, the COMT allele is important in the reuptake of dopamine and would be a reasonable choice as one of a family of alleles important to individual differences in WMC. While some studies have found a relationship between the COMT allele and WMC on some working-memory tasks (e.g., letter-number sequencing), the relationship has not been found with other tasks (e.g., N-back; Bruder et al. 2005).

Another possibility is that WMC, which I have referred to as if it were a unitary and monolithic construct, is actually composed of several correlated but different abilities that are mediated by different genotypes. It is possible that an allele such as COMT or the various dopamine transporters are associated with the skills we think of as updating information in working memory but that one or more different alleles are associated with more general attention control. For example, Reuter et al. (2007) found that COMT was not associated with performance on the ANT, even the executive attention network, but that the tryptophan hydroxylase 2 gene, a rate-limiting enzyme for serotonin, was associated with performance on the executive attention task. Many of these relatively recent gene studies suffer from problems of sample size that are compounded by the fact that they often use cognitive tasks such as N-back with unknown psychometric properties of reliability and validity.

## Conclusion

Working memory and WMC are fundamental concepts in modern cognitive psychology and in understanding why people differ on the performance of a wide array of real-world tasks. Those concepts are likely also to be important in understanding how our ancestors were able to perform such tasks as verbal and nonverbal communications, shelter building, social interactions in groups, instructing others about tasks and ideas important to the group, tool making, and artistic representation of ourselves and our world. I am confident that as we know more and more about why we differ today in WMC, both as trait and as state, it will help us better understand how that might have played a role in our own evolution.

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# Working Memory and Working Attention

## What Could Possibly Evolve?

by C. Philip Beaman

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The concept of “working” memory is traceable back to nineteenth-century theorists, but the term itself was not used until the mid-twentieth century. A variety of different explanatory constructs have since evolved that all make use of the working-memory label. This history is briefly reviewed, and alternative formulations of working memory (as language processor, executive attention, and global work space) are considered as potential mechanisms for cognitive change within and between individuals and between species. A means, derived from the literature on human problem solving, of tracing memory and computational demands across a single task is described and applied to two specific examples of tool use by chimpanzees and early hominids. The examples show how specific proposals for necessary and/or sufficient computational and memory requirements can be more rigorously assessed on a task-by-task basis. General difficulties in connecting cognitive theories (arising from the observed capabilities of individuals deprived of material support) with archaeological data (primarily remnants of material culture) are discussed.

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Perhaps the earliest systematic division between primary memory, or the “extended present,” and a secondary memory knowledge base was made by James (1890). James contrasted the subjective feeling of immediate awareness associated with the recent past with the sense of search or recollection associated with recall of events from further back in time. This subjective distinction between memory for those recent items or events that are immediately available quickly persuaded many theorists that measurement of the span or capacity of an immediate-access, short-term store might provide a direct route to measurement of intellectual ability (e.g., Baldwin 1894), and working-memory (principally digit) “span” tasks remain a feature of modern IQ tests, such as the Wechsler Adult Intelligence Scale.

By far the most influential model of working memory in the tradition of James (1890) is the eponymous working-memory model of Baddeley and Hitch (1974; Baddeley 1986, 2007), which draws heavily on research using digit span and related measurement techniques. The model proposes separate storage systems for verbal and visuospatial information (the phonological loop and the visuospatial sketch pad) overseen by a control structure (the central executive). Both systems are considered to consist of a passive storage component of relatively unprocessed material (the phonological store and

the visual cache, respectively) from which information quickly decays (in a period of 1.5–2 seconds from the phonological store; Baddeley 1986:192–196) unless covertly rehearsed by a motor program (such as subvocal or articulatory rehearsal of verbal information). Recently, the importance of integrating information from different sensory modalities has been recognized with the introduction of an “episodic buffer” (Baddeley 2000). However, the term “working memory” is of independent origin and was not originally linked either to memory for particular types of information or storage of a particular type (for additional “narrow” and “broad” definitions of working memory, see Wynn and Coolidge 2010, in this issue).

The phrase “working memory” was introduced by Miller, Galanter, and Pribram (1960) to support their concept of “Plans” as hierarchical processes controlling the order in which a sequence of operations is performed (Miller, Galanter, and Pribram 1960:16). Miller, Galanter, and Pribram (1960) speculate that “the parts of a Plan that is being executed have special access to consciousness and special ways of being remembered. . . . We should like to speak of the memory we use for the execution of our Plans as a kind of quick-access, ‘working memory’” (65). Thus, this original definition was entirely functional—a “special state or place” where a Plan is remembered while being executed and is explicitly disengaged from a wholly biological interpretation (“The special place may be on a sheet of paper”), although, of course, biological instantiations are not ruled out (“Or—who knows?—it may be somewhere in the frontal lobes of the brain”; Miller, Gal-

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**C. Philip Beaman** is Senior Lecturer at the Department of Psychology, School of Psychology and Clinical Language Sciences, University of Reading (Reading, United Kingdom [c.p.beaman@reading.ac.uk]).

anter, and Pribram 1960:65). This latter instantiation has a distinctly modern feel to it.

The utilization of a nonbiological substrate to act as a working memory has been largely ignored by psychologists inspired by Baddeley's (1986, 2007) model of essentially sensory-based internal systems. It does, however, have an obvious connection with material remains of ancient mnemonic and computational aids that have been linked to cognitive evolution (e.g., Donald 1991; Renfrew and Scarre 1998). The identification of such artifacts dates the appearance of a metacognitive awareness of the insufficiency of the internalized set of storage systems available for use as working memories (d'Errico 2001; Marshak 1972, 1991), with artificial memory systems claimed for at least as far back as the beginning of the Upper Paleolithic (d'Errico 1998). Working memory in the sense of Miller, Galanter, and Pribram (1960) is also used in artificial intelligence (AI) research to designate a component of a "production system" computer program intended to model some aspect of human cognition, notably learning and problem solving (Anderson 2005; Newell 1990). In AI terminology, the working memory of a production system holds awareness of the current state of the world, including information regarding the status of current goals or plans. Thus, at minimum, two different concepts of working memory exist: a sensory-specific, short-term code subject to decay (Baddeley) and a goal stack recording progress toward a definite end (Miller, Galanter, and Pribram 1960).

A third, and more recent, conception of working memory is as a system of attentional focus. The key idea here is that the capability to focus attention on task-relevant material and prohibit the processing of task-irrelevant material underpins performance on a large number of cognitive tasks, including tests of reasoning and fluid intelligence (Conway, Kane, and Engle 2003). Some researchers (e.g., Cowan 2005) consider focus of attention to be fixed at a given value. Cowan (2001, 2005) provides an extended argument that only four items at once can be held within the focus of attention (Miller's [1956] earlier and larger estimate of  $7 \pm 2$  requires the utilization of more, and more variable, mnemonic strategies; Cowan, Morey, and Chen 2007). Cowan also considers this value to be relatively invariant ( $\pm 1$ ) within *Homo sapiens*. Other theorists, however, argue that a specific ability to control attention determines the capacity of a working memory. For example, individual differences in scores on complex working-memory span tasks—tasks that require simultaneous, or near-simultaneous, storage and processing (for a full account, see Conway et al. 2005)—correlate with performance on a broad range of high-level cognitive tasks (Conway, Kane, and Engle 2003; Kane and Engle 2002; Kane et al. 2007) and provide the basis for assuming that whatever the complex span tasks measure has some definite and important functionality.

Cowan's (2005) view of a fixed attentional focus is not necessarily inconsistent with the controlled or "executive attention" idea, as Cowan's model also allows for an activated

portion of long-term memory outside the focus of attention to act as a short-term store. Attention is directed or controlled by an executive component similar to that proposed by Baddeley (1986), and the sum total of focal attention plus activation of long-term memory could provide the working-memory span measured by Kane, Engle, and colleagues (Engle 2010, in this issue; Kane and Engle 2002; Kane et al. 2007). Thus, under current consideration for the role of primary driver of human cognitive evolution are three dissociable theoretical constructs: the material-specific, dedicated working-memory systems proposed by Baddeley (1986, 2007); the generic and functionally defined "working memories" of Miller, Galanter, and Pribram (1960); and the increases in cognitive capability allowed by more efficient cognitive control of focal attention (Engle 2010; Kane and Engle 2002; Kane et al. 2007). Dedicated working-memory systems (Baddeley 1986, 2000, 2007) and efficient control of focal attention (Engle 2010; Kane and Engle 2002; Kane et al. 2007) comprise systems internal to the organism, whereas functionally defined working memories (Miller, Galanter, and Pribram 1960) could be internal or external in nature. These possibilities will be debated in turn, but first the *prima facie* case for *any* kind of memory improvement as a driver of cognitive evolution is considered.

## The Appeal of Working Memory for Cognitive Evolution

An internalized working memory was feted by Goldman-Rakic (1992) as "perhaps the most significant achievement of human mental evolution" (111), but the idea of internalized working memory as a single explanatory concept has also received criticism. Neath (2000) complains that the term "working memory" not only has lost its utility but also is potentially misleading. In a similar vein, Rabbitt (2001) has pointed out that the different versions of working memory proposed by various theorists are invoked as explanations for almost all research topics in cognitive psychology, while the term "working memory" remains elastic enough that several different "final" solutions to each of these topics have been proposed, each under the rubric of working memory. While the case is perhaps overstated, Rabbitt's point, that the term "working memory" loses explanatory force if used to support several mutually exclusive interpretations, is well taken. One researcher's model of how this enables higher cognitive function may differ drastically from another's, and yet both are subsumed under the same working-memory label despite being derived from different experimental situations and applied to different cognitive functions.

Given this, it is clearly necessary to indicate what is meant by "working memory" before the suggestion that its enhancement drives advances in cognitive evolution can be evaluated. First, whatever is meant must be human specific in order to



rate consideration. One recent study demonstrated superior immediate recall for the spatial positioning of digits among chimpanzees than among college students (Inoue and Matsuzawa 2007), so presumably this form of spatial/symbolic memory is ruled out of consideration on a priori grounds. Even an identifiable, human-specific mechanism holding material for subsequent processing need not necessarily reflect an evolved and dedicated “working”-memory system, however. For example, Reisberg, Rappaport, and O’Shaughnessy (1984) showed that mechanisms suitable for temporary maintenance can be conjured up or co-opted from existing resources. Reisberg, Rappaport, and O’Shaughnessy (1984) were able to increase individuals’ digit span by teaching them a mapping between the numbers 1–10 and each of their fingers. Tapping their fingers in sequence enabled these individuals, when prompted to recall, to expand their “verbal” digit span beyond the  $7 \pm 2$  normally expected (Miller 1956). The performance increase is clearly the consequence of co-opting an extant motor system in the service of the memory task. It is not clear whether the digit-motor span used in this case should be considered a part of the working-memory model as defined by Baddeley (1986, 2007), although it is unlikely to be the type of system one would wish to consider evolving and driving subsequent cognitive advance; rather, it is most likely a consequence of such advance.

One way of proceeding is to consider the a priori reasons, some of which are enumerated by Coolidge and Wynn (2001, 2004), why memory systems might be implicated in the course of cognitive evolution. The most obvious reason for considering memory to be the driver of cognitive evolution is the simple observation that the memory space available defines the type of information-processing operations that are possible in principle. Thus, a Turing machine (with infinite memory) is a more powerful device than a linear-bounded automaton (with finite memory), which in turn is more powerful than a push-down automaton (with access only to the top register of the memory stack), which is more powerful than a finite-state automaton (with no memory). By “more powerful,” I mean that it is mathematically proven that the device is *in principle* capable of more and different computations (Turing 1936). Chomsky demonstrated that the output of each of these devices can be described by a grammar (the Chomsky hierarchy) and that human languages require—at minimum—the rules of a context-sensitive grammar, which can be produced (and processed) only by a device or organism with memory capabilities comparable to those of a linear-bounded automaton or a Turing machine (Chomsky 1957, 1959; for an account couched in terms of the evolution of language, see Nowak, Komarova, and Niyogi 2002). Assuming that only a particular subset of memory, the working memory, is to be found engaging in online cognitive tasks therefore makes the characteristics and capacity of this system of critical importance in determining the information-processing capabilities of the organism, particularly with regard to language learning and usage.

Two further reasons for examining working memory as a driver of cognitive evolution are advanced by Coolidge and Wynn (2004). These are that the capacity of working memory is of “appropriate magnitude” to allow sophisticated cognitive abilities—such as contingency planning, innovation, and analogy—and that working memory is heritable. The assumption of magnitude is obviously the presumption that *working* memory is the memory system required for flexible information processing, as required by the theory of computability (Turing 1936). The heritability of working memory, however, is less informative with regard to cognitive evolution because, to take a strictly Popperian approach to scientific practice, the working-memory hypothesis cannot be falsified by heritability estimates. Heritability, variation due to genetic influence, is distinct from genetic determination, and either or both could be responsible for a cognitive enhancement of some kind in the evolutionary past.

A further and perhaps more helpful rationale for considering working memory as a contributory factor to cognitive evolution is as a basis for integrating information from several sources and as an enabler of other cognitive capabilities. Integration of information allows analogies to be drawn across domains, referred to by Mithen (1996) as “cognitive fluidity.” For example, Baddeley (2000) suggested that the integration of information could be thought of as occurring in an “episodic buffer.” Similarly, in the integrated theory of the mind in Anderson et al. (2004), there is a central matching and selection process associated with the basal ganglia that relates incoming information from perceptual modules and stored information from long-term memory to current goals, the system as a whole functioning as a working memory in the sense of Miller, Galanter, and Pribram (1960) and implemented computationally as a production system.

Integration of information directly enables cognitive capabilities, but indirect effects of an enhancement of working memory should also be considered. That is, not only should the direct benefits of a more efficient online *processor* be recognized but also the possible benefits of such a system as an *enabler* of further cognitive development must also be assessed. At this point, theories of cognition can make contact with artifacts that may themselves be products of an “enabled” cognitive system. The most obvious way in which working memory could enable cognition, and a route considered by Baddeley (2007), is in the evolution of language.

## Working Memory and the Evolution of Language

Because the phonological loop component in Baddeley’s working-memory model is held to be responsible for maintaining speech-based information over the short term, the idea that an enhancement of phonological storage is a requirement for complex language to develop is seductive

(Coolidge and Wynn 2004, 2007) and would *prima facie* seem to fit with the computational analysis of the memory requirements of language. However, the overemphasis on phonological memory is misguided in this case. Beaman (2007) reviewed neuropsychological evidence that brain-damaged patients with defective phonological storage show only subtle speech comprehension deficits. These occur only when some form of error correction is necessary for long and involved sentences. Such patients also do not necessarily show speech production deficits, querying the necessity for capacious phonological storage to support speech processing (see also Baddeley 2007:16). The use of exclusively neuropsychological data in this review was questioned (Coolidge and Wynn 2007), but it is possible to provide converging evidence from other sources that extended phonological storage is not particularly important for speech processing.

First, from computational models of sentence processing it has been shown that phonological memory *per se* is not necessary to replicate human-style complex sentence processing if other working-memory buffers, each of extremely limited capacity (one item), can be employed (Lewis and Vasishth 2005; Lewis, Vasishth, and Van Dyke 2006). Second, there is ample evidence (Kutas and Federmeier 2000; Marslen-Wilson 1987; Moss, McCormick, and Tyler 1997) that humans access meaning very quickly, beginning in the region of the first 150 milliseconds of the word (a single-syllable consonant-vowel-consonant word takes up to 300–400 milliseconds to produce at normal speaking rate). Visual recognition accesses meaning even faster (Grill-Spector and Kanwisher 2005). There is thus no need to use phonological memory because the basis for speech comprehension as lexico-semantic and syntactic codes are as readily available, and arguably more useful, than phonological codes. This is fortunate, as Baddeley (1986) estimates that the phonological component of his working-memory model remains available for only 1.5–2 seconds unless rehearsed by a late-developing and effortful subvocal articulation process. This assessment of capacity limit further suggests that phonological memory *per se* is not of sufficient magnitude to enable cognitive advance.<sup>1</sup>

An alternative account is presented by Jacquemot and Scott (2006; see also Buchsbaum and D'Esposito 2008; Jones, Macken, and Nicholls 2004) in which speech memory is coupled to a speech output buffer, with the two components ordinarily acting as a functional unit. This explains why neuropsychological patients with deficits in short-term memory for speech sounds do not necessarily show speech production errors because the speech output buffer may be unaffected. Language processing is dependent on more than memory for speech sounds, however, which is why working-memory (phonological storage) deficits can have but little effect on

everyday language comprehension. The focus on phonology reflects the seductive hypothesis that speech *sounds* are in some way special despite a lack of supporting evidence (Fitch, Hauser, and Chomsky 2005; Hauser, Chomsky, and Fitch 2002; Yip 2006). For example, Coolidge and Wynn (2007) suggest that phonological memory is a necessary prerequisite for recursion. This is a straightforward statement about the memory requirements for the appropriate classification of a recursive grammar within the Chomsky hierarchy, but the memory in question need not be phonological. Recursion does not require specifically phonological storage as claimed by Coolidge and Wynn (2007; incorrectly ascribed to Hauser et al. 2002) because it is simply a self-referential computational procedure that results in an iterative or symmetrical pattern (e.g., Corballis 2007). Recursion in language and music was long thought uniquely human (Fitch and Hauser 2004; Hauser et al. 2002), but European starlings have recently been observed to show awareness of a recursive syntax for acoustic patterns (sufficient to allow the embedding of relative clauses; Gentner et al. 2006). This interpretation is controversial (Corballis 2007)—and the starlings required a large number of trials to demonstrate even limited sensitivity to recursion—but the study shows that recursion is not necessarily limited to phonological memory and possibly not even to human cognition.

An alternative role for phonological memory in human evolution is as an enabler of language acquisition. A case can be made that phonological memory is required for vocabulary acquisition (Baddeley 2007; Baddeley, Gathercole, and Papagno 1998) on the basis that neuropsychological patients with impaired auditory-verbal storage fail to learn new phonological forms and also because nonword repetition, a developmental measure of phonological memory, predicts children's later vocabulary size (reviews by Baddeley, Gathercole, and Papagno [1998]; Gathercole [2006]). Furthermore, endocast analysis indicates that the parietal regions, the brain regions primarily associated with phonological storage (and damaged in short-term-memory patients), differ between modern and archaic specimens (Bruner 2004). However, there is at least one recorded case of impaired phonological storage in an individual who appears to have shown no difficulties in acquiring his native tongue (Baddeley 2003). Finally, the nonword repetition task requires only the immediate repetition of a single one- or two-syllable nonsense word of ca. 350–750 milliseconds duration, so although there is a clear storage requirement, it is of the kind that can be accomplished by an extremely limited (one item) buffer store of the kind envisaged by Anderson et al. (2004) or an extremely limited duration store as proposed by Baddeley (1986). Thus, although working memory of some kind is required for language acquisition, the limited phonological storage ability available cannot be considered “enhanced” relative to other hominids or to nonhuman primates, and the putative expansion of the parietal regions may be plausibly an effect rather than a cause of language development.

1. Verbal memory is more prolonged than this limited capacity, but according to Baddeley's model, this extended capacity either relies on other codes (Baddeley 2000, 2007) or is dependent on articulatory rehearsal, an optional strategy considered slow to develop (Baddeley 1986).

## Working Memory and Working Attention

If phonological working memory need not be particularly large to enable vocabulary acquisition and speech processing, what other high-level cognitive capabilities are associated with some measure of working-memory capacity? The so-called executive functions associated with the prefrontal cortex are frequently cited as the basis of higher-level cognitive capabilities in modern neuropsychological studies (e.g., Rabbitt 1997) and are associated also with working memory (Kane and Engle 2002). On purely cognitive grounds, the focus of attention is of particular interest. This may be characterized in two ways: either as Cowan's (2005) fixed-capacity attentional spotlight or as Kane and Engle's "executive attention," short-term memory capacity plus executive control (Kane et al. 2007). Focal attention, the number of items that can be "held in mind" at one time, is estimated as invariant at about four items (Cowan 2001, 2005), and this could perhaps have expanded from a lower value during the Paleolithic. However, Cowan's attentional focus can be ruled out as the origin of behavioral modernity. The value of four items was identified based on, among other evidence, the number of items an individual can "subitize" (enumerate immediately without consciously counting). Consistent with this, Tuholski, Engle, and Baylis (2001) showed that the slope of reaction time to identify the number of items up to three is flat, and beyond this there is a significant quadratic function where subitizing (and hence the focus of attention) is no longer sufficient. However, Murofushi (1997) previously reported an identical pattern in the chimpanzee, demonstrating that nonhuman primates have the same four-item capacity for focal attention as *Homo sapiens*, thus ruling it out as the cognitive basis of modernity.

Kane and Engle's (2002) idea of executive attention is a more serious competitor. "Executive attention" is an umbrella term for processes that help maintain or recover access to the memory items in the absence of focal attention or effective rehearsal strategies, for example, when a concurrent processing task prevents attentional focus remaining on the memory items (Kane et al. 2007). The behavioral task believed to tap this capability is the complex working-memory span task in which participants are required to retain and then recall a sequence of words in order when demanding processing tasks (e.g., verifying arithmetic expressions) are interleaved between the presentation of the words. An impressive set of data has been collected showing that complex working-memory span predicts individual differences on a wide range of high-level cognitive tasks (Kane and Engle 2002; Kane et al. 2007). For example, in the subitizing task mentioned above, there were significant differences between high- and low-span human participants in the speed with which they identified the number of items when that number was beyond three and subitizing was therefore no longer sufficient.

A further and arguably more impressive example comes

from a study by Hambrick and Engle (2002) contrasting the effects of age, expertise, and working memory on recall of a baseball commentary. In this study, neither age nor expertise eliminated the effects of working-memory capacity, with high-span participants reliably at the same constant advantage relative to low-span participants despite equivalent advantages of accrued expertise or decrements due to age. Crucially, however, working-memory span did not interact with expertise; high-span experts were at the same advantage over low-span experts as high-span novices were over low-span novices. Expertise did not diminish this advantage, but neither was there any runaway effect of working-memory span such that the gap between the high- and low-span individuals widened with expertise. Differences in working-memory span thus convey a consistent and constant advantage that evolution could, presumably, work with, but in this study, at least, there was no sign that the differences in working memory observed provided the basis for a step change in cognitive capability as characterizes the shift within the fossil record from archaic (e.g., Oldowan) technologies to those that signal the advent of behaviorally modern humans.

One possibility, of course, is that the step change occurred in evolutionary time and the differences in working-memory capacity within a modern human population are small by comparison—too small to interact with other advantages and enable high-capacity individuals to outstrip their low-capacity competitors by an ever-increasing margin. By this account, the shared (high) level of working-memory capacity in a modern human population is a more important source of cognitive capability than any current individual differences among working-memory scores. In this case, however, it is unclear whether complex working-memory span tasks (or similar psychometric measures) are informative with regard to cognitive evolution, as, by design, they record the effects of differences between individuals rather than the effects of elements common to all. As such, without a better model of the mechanism involved, it is not clear whether the differentiating elements of the span task are picking up on the more efficient use of a single system or whether the species-common capability is actually a different system or process from that measured by the individual difference scores (Borboom and Dolan 2006).

## Working Memory and the Pursuit of Goals

To summarize, two internalized views of working memory have been considered. The idea of an enhanced phonological storage component can be rejected as unnecessary for the development and comprehension of language; although the neuropsychological data suggest that some such storage is required, the capacity and duration of this storage need only be quite restricted. A domain-general-executive-attention mechanism distinguishes between low- and high-capacity individuals on a number of high-level cognitive tasks and there-

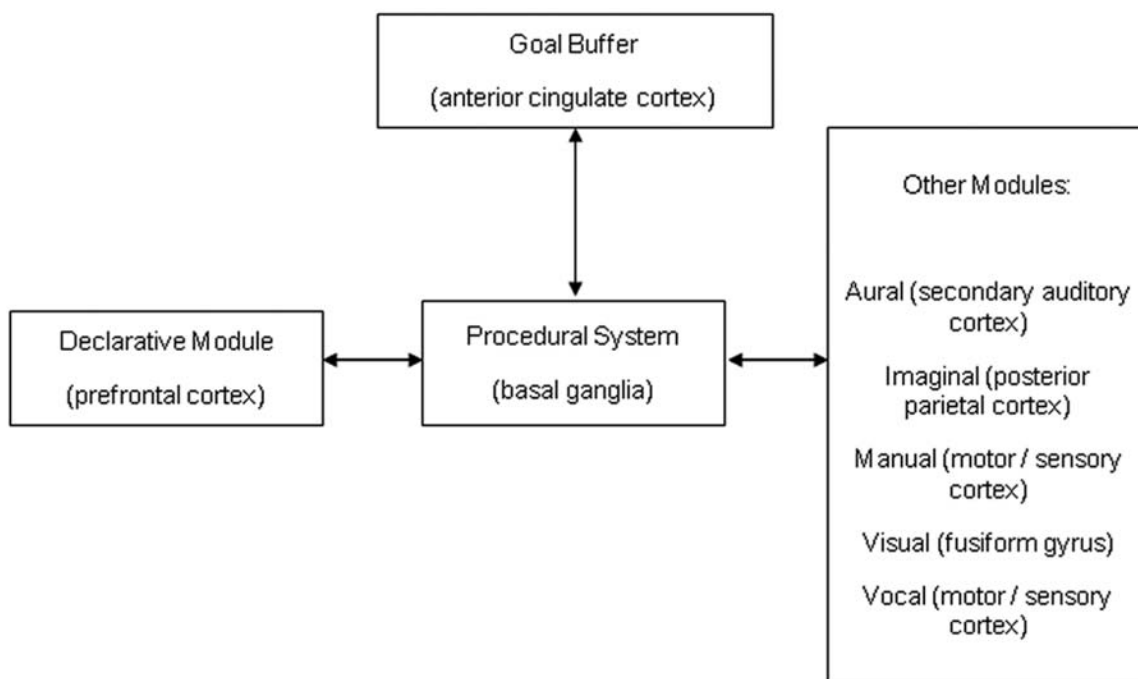


Figure 1. Adaptive control of thought-rational (ACT-R) model 6.0 (version from 2007). The core of the model is the relationship between the goal buffer (a kind of working memory in the sense of Miller, Galanter, and Pribram 1960), the declarative module, and the procedural system. Other modules that may be viewed as similar to Baddeley's (1986) "slave" systems also serve as temporary maintenance devices, but each is of extremely limited capacity.

fore remains a possibility as a necessary development for cognitive evolution to progress. However, it is unclear whether such a mechanism is sufficient to account for the emergence of behavioral modernity among anatomically modern *Homo sapiens*. The third alternative is the development of a more general "working"-memory system in the sense of Miller, Galanter, and Pribram (1960), of allowing quick access to goal-relevant information. The distinction between this and executive attention is subtle but informative: executive attention refers to the ability to maintain goal-relevant information in the presence of irrelevant distracters (Kane and Engle 2002; Kane et al. 2007; although not all distractions are suppressed by high-span individuals [Beaman 2004]) and is a capability associated with the control functions of the prefrontal cortex. The more general view makes no reference to the requirement to inhibit task-irrelevant distracters and allows for the locus of the information to be based either internally or externally.

The most detailed modern version of such a view is the adaptive control of thought-rational (ACT-R) model devised by Anderson and colleagues as an integrated model of cognition (Anderson 2005, 2007; Anderson et al. 2004). A "unified" model of cognition such as this has the advantage that it is possible to relate such things as the capacity of working-memory buffers to performance on complex cognitive tasks

and to restrict cognitive capabilities by enforcing or relaxing such constraints (Anderson and Lebiere 2003; Cooper 2002; Cooper et al. 1996; Newell 1990). ACT-R is employed here as an exemplar of what might be achieved without any necessary commitment to its detailed assumptions.

Each of the buffers in Anderson's ACT-R model is of restricted (one item) capacity, so any evolved enhancement must be associated either with the development of new buffers (cf. Barnard 2010, in this issue; Barnard et al. 2007) or some other factor. In the current version, the goal module, which drives behavior, is assumed to be located within the anterior cingulate cortex. A further control structure is the declarative module, and the means by which the system communicates information about progress toward the goal is via the basal ganglia, a subcortical structure that maps cortical buffers to each other (see fig. 1).

The basal ganglia is the central bottleneck in information processing according to this theory, a position that has recently received support (McNab and Klingberg 2007; for a related theory, see also Hazy, Frank, and O'Reilly 2007). However, although it plays a critical integrative function and hence acts in many ways as the nucleus of a "global work space," it is not a candidate for the basis of cognitive evolution. First, it is an evolutionarily old structure critical for basic as well

as advanced functions. Second, it maintains no memory buffer itself (in this respect it resembles Baddeley's concept of a central executive, except that its role is communication rather than management). Enhancement via cognitive evolution can therefore occur within this system only if the communication system is made more efficient (in terms of speed and fidelity of transmission, as seems to have happened earlier in mammalian evolution) or if previously separate cognitive modules are connected together to work in concert toward a centrally represented goal. Differences in speed of communication (speed of processing) have been implicated in studies of individual differences in modern human intelligence (e.g., Anderson 1992), but these will not be considered here. Likewise, the possibilities of evolving new modules and connecting these to a central engine of cognition are also sufficiently familiar (e.g., Barnard 2010; Barnard et al. 2007; Mithen 1996) to require no further consideration at this point.

Arguably, the most interesting area of speculation concerns memory for current goals. Anderson (2005, 2007) speculates that the goal module enables disengagement from basic wants and drives (goals) and focuses on something else (the means). That is, it allows the individual to disengage the immediate circumstances as experienced and consider how to create something more desirable. Previous theorists (e.g., Papineau 2001) have suggested that means-end reasoning of this type distinguishes human from nonhuman reasoning, and early pioneers in the psychology of human problem solving likewise focused on the ability to perform means-end analysis (Newell and Simon 1972). Means-end analysis differs from simpler forms of problem solving in requiring an ability to form and maintain subgoals. It is also a more powerful form of problem solving than simpler alternatives, such as difference reduction, because the flexibility of means-end analysis allows the means to become (temporarily) the end. In contrast, difference reduction involves making incremental steps to reduce the difference between the current state and the goal state. Although this approach is frequently used in human problem solving, it causes problems when all courses of action appear to lead away from the goal state. Jeffries et al. (1977) observed the use of difference reduction in the well-known hobbits and orcs (previously missionaries and cannibals) river-crossing problem. In this study, about one-third of participants chose to undo their previous move rather than take a move that seemed to be a movement away from the solution (i.e., violate difference reduction). Reluctance to abandon difference reduction can make some problems unsolvable. MacGregor, Ormerod, and Chronicle (2001) suggested that insight into the nine-dot problem, a particularly difficult problem that requires creative insight to solve, is impeded by use of difference reduction and limited look-ahead. Faced with the limitations of difference reduction, Newell and Simon (1972) suggested that human cognition might follow the principle of means-end analysis as follows: (1) set up a goal or subgoal; (2) look for a difference between the current state and the goal or subgoal; (3) look for a procedure, *including setting a*

*subgoal*, that will reduce or eliminate this difference; (4) apply the procedure; (5) repeat steps 2–4 until the final goal is achieved.

It would be of interest to examine the archaeological record to determine what patterns of behavior can be identified that are unlikely to emerge in the absence of means-end analysis (Mithen 1990). However, it seems implausible that the construction of any material artifact or technological culture of any complexity would be possible in the absence of some degree of subgoaling. Means-end analysis per se is therefore an implausible candidate for the basis of behavioral modernity. However, the extent to which subgoals can be maintained and the motivation for doing so are both worthy of further examination.

The extent to which goals and subgoals are maintained is a critical feature of cognitive control, albeit one that has generated empirical research only recently. The parent goal must be maintained while subgoals are formed and achieved (the declarative module is used for this; Anderson 2007), otherwise a prolonged sequence of coherent action would not be possible. Goal stacks are employed in AI research as a programming convenience; however, there are indications that subgoals and their resolution correspond to some psychological reality and have measurable behavioral consequences (Anderson, Kushmerick, and Lebiere 1993). The depths to which subgoaling might proceed and the possibility that goal memory, like other forms of memory, might be susceptible to interference and forgetting have only just begun to be explored (Altmann 2002; Altmann and Trafton 2002). Failure to subgoal has, however, long been associated with the performance of neuropsychological patients with frontal lobe damage on tasks requiring advanced planning (e.g., Goel, Pulara, and Grafman 2001). A restriction on the depth to which one can subgoal, or the extent to which parent goals can be maintained while pursuing subgoals, is likely to have a profound effect on the mental operations for which one is adequately equipped. The latter situation, for example, virtually defines the difference between high- and low-working-memory-span individuals in the executive-attention theory of Kane, Engle, and colleagues (Kane and Engle 2002; Kane et al. 2007).

The analysis of behavior in terms of necessary subgoals is also conceptually similar to the "conigram" representations introduced by Haidle (2010, in this issue), but it can result in different conclusions. Two examples illustrate the relationship. Haidle presents a conigram for the use of a tool set to extract termites by *Pan troglodytes* and a further conigram for the use of an Oldowan tool to cut meat. Both examples are presented in terms of a main goal and three subgoals (subproblems) that are solved in turn over seven different phases. These behavior patterns can also be analyzed using techniques from the literature on human problem solving to suggest how the problem space is traversed and the goal state attained. In simplified form, a part of the termite extraction task might be expressed using production (if-then) rules as follows:

```

Set a goal to obtain termites
  IF goal(termites)
  and inaccessible(nest)
  THEN set a goal to open the nest
    IF goal(open,nest)
    and not available(probe)
    THEN set a goal to construct a stick tool
      IF goal(construct,stick tool)
      and available(twig)
      THEN detach(twig)
      shorten(twig)
      remove(leaves,twig)
      and the goal is satisfied
    IF the goal is to open the nest
    and available(probe)
    and available(chisel)
    THEN push(nest,chisel)
    and the goal is satisfied
  IF goal(termites)
  and accessible(nest)
  THEN extract(termites,probe)
  and the goal is satisfied

```

This quasi formalism represents a much-reduced and simplified version of the task (e.g., the search for a stick, a non-trivial task in itself, is omitted) for purposes of space and clarity, but, nevertheless, by indenting the formation of the subgoals, the recursive nature of the problem solving and the number of goals that must be maintained simultaneously in working memory become more immediately apparent (no more than three at any one time in order to satisfy the main goal). It is also worth noting that by representing the skill set (the operations conducted in the THEN part of the rule) as responding directly to currently perceived requirements (the IF part of the rule), the need for forward planning and other “executive” functions is revealed as potentially lower than that suggested by Haidle (2010). Compare the above with the (again, much simplified) minimal set of production rules necessary to begin to use an Oldawan tool to cut meat:

```

Set a goal to consume meat
  IF goal(consume,meat)
  and meat
  and requires(cutting,meat)
  THEN set a goal to cut the meat
    IF goal(cut,meat)
    and not available(cutting_tool)
    THEN set a goal to construct a cutting tool
      IF goal(construct,cutting tool)
      and available(raw_material)
      and available(hammer_stone)
      and not shaped(raw_material)
      THEN set a goal to knap the raw material with
      the hammer stone
        IF goal(knapped(raw_material,hammer_stone))
        THEN position(raw_material)
        position(hammer_stone)
        strike(raw_material,hammer_stone)
        turn(raw_material)

```

In comparison with the procedure for using a single tool to obtain termites, even in simplified and much-curtailed form, this second algorithm requires a minimum of four sub-

goals to be held in mind simultaneously to reach the point of beginning to knap the putative tool with the hammer stone (how many further subgoals are then required to work the stone is unclear). This is because of the iterative depth of the procedure—each application of an operator required to reach a subgoal adds that subgoal onto the stack of elements to be held simultaneously “in” working memory. Subdividing a task into the subgoals necessary to reach the goal state by means-end analysis thus reveals the complexity of some superficially simple tasks (and *P. troglodytes* are revealed as recursive means-end reasoners). More pertinently, the load on working memory (in the sense of Miller, Galanter, and Pribram 1960, although not necessarily in the senses of Baddeley 2007 or Engle 2010) is shown to be, not surprisingly, higher for hominid production of Oldawan tools than for the chimpanzee’s use of sticks to obtain termites. The general view that Oldawan stone tool production is behaviorally more complex than probing a nest of termites with a stick and chisel is, of course, consistent with Haidle’s (2010) analysis, but the decomposition of the task into a set of subgoals reached by means of applying well-defined procedures suggests that the relative contribution made by memory per se is greater than is obvious from a cognigram. Advanced planning and executive control might, in consequence, be less necessary. This is especially the case if the computational demands on the individual can be lessened by considering how the physical and social environments might support and hence simplify some of these procedures (e.g., the presence of perforators next to termite nests in the first example; for examples from cognitive science, see also Brooks 1991; Kotovsky, Hayes, and Simon 1984; Simon 1992). Further analysis of the knapping procedure itself is also doubtless possible but requires further study, and the task is also likely to require the involvement of visual/motor modules to track progress at the task toward the eventual goal (Stout et al. 2008).

The motivation for pursuing subgoals as well as the ability to do so is an issue that is also worth pursuing for its own sake. The cognitive science of planning and problem solving has largely focused on “cold” (unemotional, propositional) cognition that lends itself to computational modeling, but arguably the defining features of behavioral modernity are associated with “hot” (emotional, meaning-laden) cognition (P. Barnard, personal communication) or, as Mithen (1996) depicts it, the beginnings of art, religion, and science. These activities, which are pursued for their own sake rather than to advance some longer-term goal, are more associated in the literature with decision making than with problem solving and with ventromedial rather than dorsolateral areas of the prefrontal cortex. At first blush, many of these more pleasurable aspects of modern life (art, music), taken for granted within both urban and hunter-gatherer societies, seem entirely useless from a strict evolutionary viewpoint. However, the point is not whether art or music itself fulfills an evolutionary purpose but rather whether the motivation toward music—or any other seemingly nonadaptive goal—is reinforceable.

Although it is difficult to trace the emergence of music in the archaeological record, the emergence of behavioral modernity is indicated by the appearance of traits that reveal the presence of symbolic thought that—by themselves—may convey little or no obvious evolutionary advantage. Thus, although some forms of technological advance (e.g., in the design of hand-axes) show obvious survival advantages, other indicators of behavioral modernity, such as the appearance of cave art, provide no such succor. Self-rewarding activities such as art, craft, ritual, and music may have been subject to the rigors of sexual selection (e.g., Miller 2000), but something must have initiated this in the first instance. The motivational system that led to the conception and execution of such undertakings, coupled with the ability to represent subgoals and indulge in means-end analysis, would seem to provide the necessary mechanism to pursue these activities.

### Hot Cognition and the Establishment of Goals in Working Memory

In brief, the current suggestion is that something must act to provide a goal and the motivation to reach that goal must be maintained as well as the goal itself. The traditional analysis of problem-solving behavior within cognitive science assumes that subgoals are merely stepping-stones on the way to a parent goal as defined by the programmer (AI research) or the experimenter (cognitive psychology). Outside of these highly unusual settings, however, both goals and subgoals are set by individuals on the basis of their intrinsic reward status. Reinforcement learning, as exemplified by classical conditioning, predicts that subgoals satisfactorily realized in the course of achieving a parent goal are themselves subject to reward. In this way, reward-predicting states (subgoals) shift to become rewards in themselves. The brain thus learns value proxies for evolutionarily important goals such as food or sex—and such lower-value goals then receive the neurochemical reward “hit.” Montague (2006) points to the dangers of this system for establishing and maintaining dysfunctional behaviors such as ritual hand washing in obsessive-compulsive disorders. However, by the same token, the system is also powerful in enabling the production of less dysfunctional, but perhaps no less ritualistic, behavior patterns. Like both language and means-end analysis, this relies on recursion to achieve its most powerful effects. A goal acts as a reward, and states associated with the reward (subgoals and operators that lead directly to the goal) then become reward giving in themselves, representing by proxy the reward value of the parent goal state. Thus, an increased capability to subgoal could lead to an increased behavioral repertoire by increasing the desire to meet such subgoals independently of their association with a parent goal. Montague’s suggestion is that subgoals, or operators, that are reliably associated with a reward signal become an end in themselves. The development of cave art or music (and even, perhaps, aesthetically pleasing stone tools or handaxes) may begin as a behavioral pattern that is re-

inforced because of its association with the accomplishment of other goals (e.g., sexual selection) but rapidly becomes a goal in itself. This analysis says more about the *development* of modern thinking than its origins, but a similar criticism has been repeatedly made of Darwin’s *Origin of Species*, which also speaks to development (by means of evolution) and has little to say on origins per se. Focusing on possible means of development might, eventually, yield insights into ultimate origins. Once it is a goal in its own right, a particular outcome or behavior pattern can be pursued or repeated at a future date, subject only to the capacity to maintain multiple goals and the constraints of mechanisms that exist to preferentially order goals and activities. If these mechanisms are insufficient, then these behavior patterns are unsustainable over the long term. Thus, identifying mechanisms that are necessary to drive the development of complex behavior also identifies the ultimate origin of those behaviors at the point at which these mechanisms became available.

### Connecting Cognitive Archaeology and Cognitive Psychology

The brief review given above provides a flavor of the types of working-memory or working-attention theories currently extant within cognitive psychology and considers how the theoretical constructs involved might have been involved in later hominid evolution. However, many forms of working memory are necessary for successful action within a natural environment (e.g., spatial working memory, yet another form of working memory, is investigated by researchers examining the ability of rats to navigate a radial maze), and the interaction between the cognitive system and the environment deserves more consideration than it has traditionally received within cognitive psychology. The experimental situation that has given rise to the kinds of theories considered here usually involves isolating an individual from its peers and examining its cognitive capabilities while also restricting the tools or artifacts available. Logistic constraints also mean that experiments typically last under 1 hour. A span task, for example, will take less than 1 minute per trial to administer, with anything from 15–60 trials being run in a single session. It is therefore not surprising that much of cognitive psychology addresses mental operations specific to an individual and lasting over very short time spans. Short-term memory, for example, is generally considered to last for no more than a few seconds and is widely studied, but all longer periods of time are covered by long-term memory with distinctions between long-term memory of a few days and several years being drawn only rarely.

In contrast, the data typically considered by archaeologists are in the form of remnants of material culture, the product of multiple minds and unknown time spans. One would guess that in many cases, the operation of mental processes that produced these artifacts is generally over a greater time period than those typically studied in the laboratory. Enhanced per-

sonal short-term memory therefore seems in many ways an odd thing to propose as a necessary precursor for these material products of long-term and collaborative labor. To be fair, anthropologists recognize the difficulties of inferring cognitive capabilities and process from inanimate artifacts, and fossils and other methods, such as comparative studies of nonhuman primate behavior, are well established. For the emergence of modern thinking, however, the traits used to identify modern human behavior are primarily inferred either from artifacts, such as art, ornamentation, blade technologies, worked bone and antler, complex hearth construction, and others, or else from necessarily social tasks, such as effective large-mammal exploitation and expanded exchange networks (see Henshilwood and Marean 2003, table 1). These are all equally distant from the situations typically engendered and examined within the experimental psychology laboratory. This is as much a problem for the experimental psychologist as for the cognitive archaeologist.

There has as yet been comparatively little research directly examining the influence of factors such as short-term memory or executive attention on vigilance or longer-term concentration (although it is known to affect long-term learning), but this is certainly an avenue open to exploration. Applying standard techniques of experimental psychology (e.g., performing under memory loads and other “dual task” manipulations intended to use up particular cognitive resources) to experimental archaeology (such as flint knapping and the reproduction of other artifacts) could also go some way to determining the extent to which, at least among modern humans, the production of such artifacts benefits from inner speech capabilities and short-term memories.

In terms of some of the specific ideas advanced here, there are various ways of shifting from the current “just-so story” level of theorizing to a real, falsifiable scientific hypothesis on four different levels. One could examine the coherence of the subgoaling hypothesis suggested in the latter part of this paper by running a series of computational studies to determine whether reinforcing subgoals within an existing cognitive architecture (such as ACT-R) is a plausible development of such architectures. One could also take verbal protocols from, for example, experienced flint knappers to identify goals and subgoals and how they are managed within the design problem space of lithic tool manufacture. A third suggestion is to search within the existing fossil record for traces of behavioral patterns that might be usefully described, or redescribed, in information-processing terms of problem spaces, means-end analysis, or subgoal resolution, expanding on the approach earlier applied, rather cursorily, to termite extraction and Oldowan tool manufacture. A final suggestion is that for any architecture that maps the cognitive components onto a neural substrate (as later versions of ACT-R do), neural development in those brain regions associated with goal selection and maintenance would be expected and might be looked for in endocast and other studies (Bruner 2004).

Not all these suggested avenues of study are of equal value,

of course (to an experimental psychologist, duplicating archaic activities under modern conditions has a distinct appeal), but each would go some way to examining the viability of the subgoal-reinforcement hypothesis. A similar approach could be taken with other working-memory hypotheses of cognitive evolution, provided that the working memory in question was sufficiently tightly defined a priori.

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# From Executive Mechanisms Underlying Perception and Action to the Parallel Processing of Meaning

by Philip J. Barnard

The dominant conceptualization of working memory distinguishes mechanisms that handle auditory-verbal and visuospatial representations from central executive resources that control and guide them. A straightforward case can be made that executive mechanisms evolved initially in the service of directing attention to salient environmental stimuli or events and selecting adaptive actions under the guidance of affective markers. In this paper, “working-memory capacity” is viewed as an emergent property of interactions between specialist subsystems with no homunculus-like executive. Mental capability could well have advanced via the differentiation of a single multimodal subsystem into additional new specialist subsystems that process not just verbal and spatial representations but also subsystems specialized to manipulate different kinds of meaning. The resulting overall mental architecture would devolve control of action and speech to peripheral mechanisms while allowing central subsystems to focus attention and decision making on meaning. According to this hypothesis, increased mental capability is dually based on the development of more abstract representations *and* on the observation that the more subsystems there are, the more the mind can do at one and the same time: only the most advanced mental architecture can control walking, talking, and thinking at one and the same time.

From the dawn of the computing age, psychologists (e.g., Craik 1943) and others (e.g., Von Neumann 1958) have used computational metaphors to help us think about animate minds. It is straightforward to consider ideation as involving “information” either derived from sense receptors or retrieved from memory. Mental processes, like computer programs, act on that information to generate instructions for controlling physical actions or to update mental representations associated with cognitive operations, such as those involved in language and thought. Most computers available in the 1970s had “Von Neumann” architectures: a central processor, a small random-access memory holding information that was currently being used, and more permanent stores of greater capacity—on tape or disk—whose content could be searched and retrieved when needed. An “operating system” controlled when programs ran and how they utilized hardware resources. The original conceptualization of working memory (Baddeley and Hitch 1974) was cast in that context. Observed variation in what we recollect in the short term was viewed as arising

from the flexible use of verbal and visuospatial storage components controlled by a central executive (Baddeley 1986, 2007). Modern computers are a far cry from early computers. It is not unusual to have many processors networked together, where the individual processing units are self-contained and interact according to communication protocols in which there is no “central executive” controlling their collective operations.

The list of things that might set modern humans apart from earlier hominins can no longer be counted on the fingers of two hands. In one recent review, Amati and Shallice (2007) include language, tools/instruments, signs/signals, dynamic concepts, aesthetic sense, metarepresentation, algorithmic capacity, categorization/organization, theory of mind, and anticipatory planning. Computer metaphors have often been used in the literature on the evolution of the human mind to explore how such capabilities arose out of more primitive mental abilities. Did they arise as a result of new domain-specific processing modules that capitalized on evolutionarily ancient mechanisms for action selection and emotion (Sperber 2002; Tooby and Cosmides 2000)? Did they rely on some more domain-general capability such as general intelligence or cognitive fluidity acting over a range of specialized intelligences (Mithen 1996)? Were they made possible by some

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**Philip Barnard** is on the research staff of the Medical Research Council Cognition and Brain Sciences Unit (15 Chaucer Road, Cambridge CB2 7EF, United Kingdom [phil.barnard@mrc-cbu.cam.ac.uk]).

late change in a processing resource, such as phonological storage, that resulted in enhanced working-memory capacity (Coolidge and Wynn 2005)? Did a novel computational element evolve for controlling sustained, nonroutine, and multilevel mental operations (Amati and Shallice 2007)?

Here, I discuss the hypothesis that modern thinking emerged as the last step in a systematic series in which basic mammalian minds were augmented by successive additions of one new subsystem. The “system-level” approach is one instantiation of the idea that modern humans have enhanced working-memory capacities. Capacity will be presented as an emergent property of interactions among subsystems in the absence of a homunculus-like executive. Unlike the massive modularity viewpoint, subsystems deal not with packages of domain-specific “knowledge” but with different types of information, as with the phonological and visuospatial encodings of information in working-memory theory.

I shall first present a theoretical perspective on the “working memories” of the common ancestor of great apes and modern humans. Thinking about the computational complexities of human ideation is not easy. Accordingly, the next section will introduce some concepts to help understand how networks of intercommunicating subsystems can provide successively enhanced mental capabilities. It examines how networks with distributed control hold information in memory, attend to mental images, and realize wider executive functions for controlling actions in the world. The subsequent section will trace a trajectory in which further subsystems could have been added across the hominin line. Throughout, the emphasis will be on examining in theory what kinds of properties would hold for “working-memory capabilities” as mental architecture undergoes successive differentiation. A final section discusses some implications of this analysis for archaeological enquiry.

## A Multiprocessor Perspective on the Evolution of Cognitive Capabilities

A straightforward case can be made that cognition evolved to coordinate effective action (Glenberg 1997) and that the evolutionary origins of our “executive” mechanisms are present in any mammalian mind capable of learning. We can assume that a “basic” mammal has multiple sensory capabilities and a repertoire of actions supporting both survival of individuals and propagation of their species. Attending to relevant environmental contingencies and selecting actions that are adaptive in context are central. Figure 1 shows a four-subsystem architecture, with three subsystems specialized to process sensory information (acoustic, visual, and body state) and a fourth subsystem to synthesize information over all these domains (multimodal).

Several notational features of the diagram require elaboration. Black arrows represent information flow—incoming from sense receptors, flowing from one subsystem to another or from a subsystem to bodily effectors, whether they control

somatic or visceral states or movements of the head or limbs, and so forth. Subsystems share a common template. The horizontal dumbbells index processes that generate the information content that is transmitted to another part of the system. Each subsystem not only takes inputs and generates outputs but also has its own “memory,” and this is composed of a number of parts. The darker horizontal rectangle indexes a process that creates an image of recent input—what we humans would consciously experience as sights and sounds in the world and sensations in our bodies or, in the case of the multimodal image, what we more widely “feel” about what is going on and how to react. These images are not static pictures. They have temporal extent—they contain the dynamics of changes in information states—what we would experience as the swaying of tree branches in the wind, the rustling sound of foliage in motion, or the brushing of a twig against our skin.

Behind each image is a multilayer structure labeled “memory.” This last component extracts regularities that underlie information patterns over segments of time as represented in an image. This memory is in continuous operation “in the background” and supports learning. It is important to note that “learning” in this scheme occurs in a specific mental domain. The sensory subsystems collectively support what has classically been known as “perceptual learning,” while the multimodal subsystem would learn about co-occurrences of different sensations—as when classical conditioning associates sights, sounds, or bodily actions with reward or pain. Nothing “smart” occurs in these memory components—they allow patterns to be completed or predicted just on the basis of what had regularly co-occurred with what in the past, namely, statistical learning. By completing missing information in sensory or multimodal patterns, memory simply acts to augment whatever is conveyed by current sensory stimulation.

The final notational point is that the component in the multimodal subsystem that is generating the flow of information to the skeletal muscles is configured differently from all others. This process (fig. 1, *black shading*) is sourcing information from the image that contains the pattern of multimodal data. In computational terminology, it is working on a buffered trace of information. All other processes throughout the architecture are being driven by moment-to-moment changes in direct input to a subsystem. The buffered trace may also be augmented by pattern completion from the memory system behind it. This buffered state is equated with the mind attending to some aspect of multimodal information while all other processes are on something akin to “autopilot.” If figure 1 were now redrawn with the process that is buffered located in one of the three sensory subsystems, the “system” would be attending to a sensory stream, much as when we attend to the sound of person speaking, to a particular object in our visual environment, or to bodily sensations in our hands.

We can pinpoint three attributes of the “working memories” of a four-subsystem architecture for a prototypical mam-

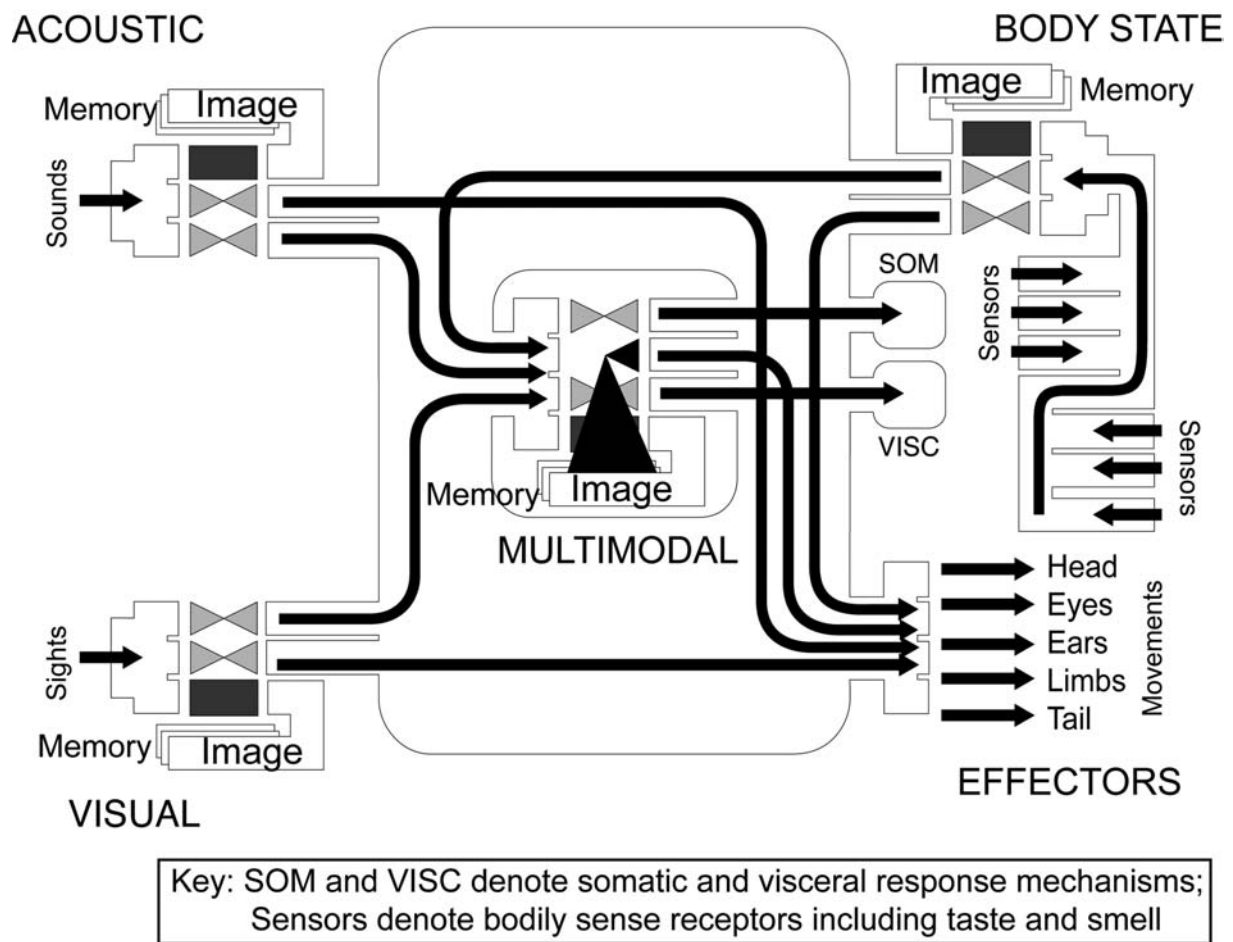


Figure 1. Four-subsystem mental architecture.

mal, such as a zebra (fig. 1). First, there are parallel routes through which action can be guided. There are flows from the sensory subsystems directly to the effectors—a change in a sensory pattern can determine an action such as moving the head or a limb in response to a loud sound, a rapidly moving object on a collision course, or a sudden pain. Second, the processing of a multimodal synthesis of information fulfills functions often assigned to “a central executive,” even though it works no differently from other subsystems. Were the current multimodal state to represent danger, foraging responses can be inhibited and escape responses facilitated via the flow of information from the multimodal subsystem to the effectors. Working memory is a composite of four dynamic images whose content is subject to both selective attention and optional augmentation by pattern completions from more permanent memories. Working-memory capacity is best viewed as an emergent property of the whole system as its components interact with one another over time. Nothing “decides” what to do—actions arise out of multiple distributed constraints.

The third point concerns abstraction. Sensory images rep-

resent the details of what is seen and heard in the world or about current body states. However, what sensory processes pass on to the multimodal subsystem is selective and involves discarding detail. A process passes on a summary of the underlying form of selected parts of the full-sensory scenery. Fine-grained visual properties are discarded when passing on a summary of the overall structure of an object or movement trajectory—the deeper patterning of invariants in the image. This allows the multimodal subsystem to work on a more compact encoding of information than the sensory ones. Its image content encompasses “longer” sequences of changes over time than those of sensory subsystems. The memory system behind the multimodal image is extracting second-order regularities over the first-order ones originating in the sensory subsystems. There is nothing one would want to describe as “cognitive” occurring in this architecture. The architecture is consistent with an evolutionary old role for emotions and learning in guiding adaptive behaviors in which multimodal processing uses affective (Barnard and Teasdale 1991) or somatic (Damasio 1994) markers to augment action selection.

Figure 1 is actually a scaled-down version of a proposed nine-subsystem human architecture whose properties I have explored over the past 2 decades. The internal arrangement of the components within all subsystems was originally derived to accommodate evidence from a range of verbal, visual, and cross-modal short-term memory tasks, as well as those involving language understanding and production (Barnard 1985, 1999). In particular, arranging the image and memory components in parallel with the processes that pass information among subsystems was consistent with classic findings in neuropsychology that impaired short-term memory still enabled new material to be encoded in long-term memory. Among the explicit principles that constrain how subsystems work are the following: any one process can do only one thing at a time (e.g., focus on what a single speaker is saying), buffering can be at only one place in the architecture at any given moment (focal awareness), and images have a limited temporal extent. The full nine-subsystem architecture (fig. 6) has also been extensively evaluated in relation to evidence concerning relationships between cognition and emotion in both normal healthy individuals and those with various psychopathologies (Barnard 2004; Barnard and Teasdale 1991; Teasdale and Barnard 1993). While the vast bulk of work in experimental psychology tends to focus on laboratory tests of theories relating to specific mental capabilities, such as perception, memory, language, or reasoning (microtheories), this approach to mental architecture seeks to capture the entire mental system (macrotheory). A macrotheoretic approach is of particular value in many applied settings in which relationships between different facets of mental life need to be addressed in the analysis of day-to-day tasks, be they current (Barnard et al. 2000) or those carried out by our hominin ancestors (Barnard 2010).

If we suppose that later hominin minds contain more than four subsystems, then there must have been a mechanism, akin to cell division in biology, that enabled the emergence of additional subsystems. We have recently offered a detailed proposal for such a mechanism (Barnard et al. 2007). Here, I will rely on an outline of that mechanism, rather than its detail, sufficient to allow discussion of how the working memories of earlier hominins may have been successively enhanced.

Figure 2 shows a mental architecture composed of six rather than four subsystems. The additions are labeled the “effector” subsystem and the “spatial-praxic” subsystem. The effector subsystem now mediates control of the skeletal musculatures peripherally rather than directly from the multimodal subsystem, as in figure 1. In the case of a monkey with considerable manual dexterity and the capability to move through an arboreal environment, there are huge demands for the rapid and efficient coordination of limbs, center of gravity, and grasp, and a large fraction of the multimodal subsystem would be required to do that. Given that complex skeletal coordination occurs across all kinds of settings and mood states, it is not hard to see how the workings of the underlying

neural circuitry required to achieve such coordination could become statistically separable from all other multimodal contingencies. The intricate coordination of limbs and finger movements over time, as well as their configuration in space, would come to depend on invariants in the visual environment independently of the details of the specific setting, the agent’s bodily state (such as hunger), or specific cues in the auditory scene. This would enable a fifth functionally independent subsystem to emerge that meets the greater demands for motor coordination not faced by animals with simpler repertoires of fixed action patterns (e.g., walk, trot, turn head, bite). With a fifth subsystem in place, the multimodal subsystem no longer needs to control the details of muscle action. Rather, it can send an index such as “jump,” and the details of muscular coordination are handled by the new subsystem, along with its allied parallel inputs from vision, audition, and body states. A five-subsystem architecture is not shown here, but it contains all the flows in the six-subsystem architecture (fig. 2, *gray shading*), without the additional flows of information going into and out of the spatial-praxic one (fig. 2, *black shading*). The presence of a fifth subsystem was seen as a precondition for a vital evolutionary development of a sixth subsystem to emerge that captures a more abstract representation of spatial praxis (Barnard et al. 2007).

Consider the action of twisting a fruit to break the stem holding it to a branch. What is seen is that the hand and fruit would both turn in three-dimensional space. At the same time, the muscles would control a set of postural changes that are perfectly correlated in time with the visual changes, albeit at short lags. The multimodal image and the memory system behind it together enable such correlations to be abstracted from the direct feed of summaries of information from the visual subsystem and the feedback from the body-state subsystem. Given a range of correlations specifically involved in manipulating objects and moving in the world, the potential now exists for a higher-level “mental code” to emerge, not this time for coordinating muscle systems but for representing just that second-order material in the multimodal image that deals with visuospatial control of actions. What the motor action of twisting and the visual pattern of turning have in common is a second-order invariant property—“rotation at some variable rate.” At the point at which a collection of invariants, as with the earlier emergence of a fifth subsystem, becomes statistically independent of other multimodal invariants, the processing capability of the multimodal subsystem splits into two. This time, instead of a new peripheral subsystem emerging, a new “central” subsystem emerges that mediates the visuospatial control of action. The technical detail of the separation mechanism documented by Barnard et al. (2007) leads two interacting central subsystems. Importantly, the general mechanism they propose requires only a gradual succession of tiny alterations in connectivity within underlying neural circuitry for the separation to ultimately come about and, subsequently, for the new subsystem’s functionality to develop.

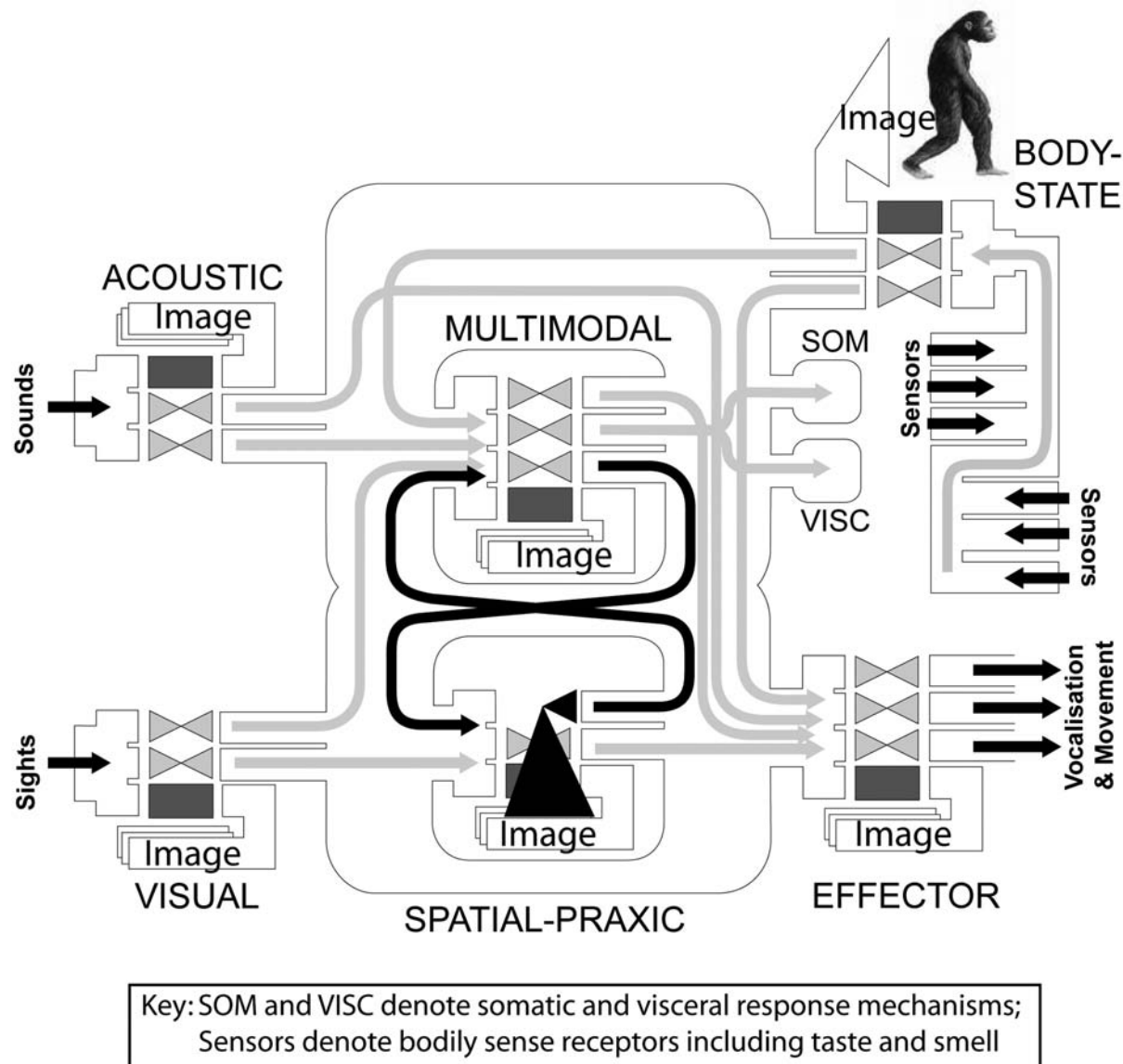


Figure 2. Six-subsystem mental architecture. The body image component suggests what the body might be (modified from Barnard et al. 2007).

The working-memory capacities of species with this architecture would be augmented relative to precursor architectures. Obviously, more processes are active at the same time. As with the four-subsystem architecture, there are lines of communication from sensory to effector subsystems, flows from the sensory subsystem to the multimodal subsystem, and flows from this subsystem to the effector subsystem. However, there is now an *additional* processing loop between the multimodal and spatial-praxic subsystems, reciprocally linking their inputs and outputs. This arrangement is similar to the visuospatial scratch pad controlled by a central executive within the classic working-memory model. Note that the current spatial-praxic subsystem incorporates an addi-

tional function—an independent process mediates another flow from vision to the control of skeletal action. The multimodal subsystem not only modulates effector action directly but also can concurrently generate abstract spatial-praxic forms that are projected into a new, purely “internal” mental image. The multimodal system retains its use of evolutionarily ancient markers of affect to guide action selection. It follows in this arrangement that attention can be directed internally at aspects of form independently of their affective significance, and this is indexed in the figure by the “buffering” of the process linking the spatial-praxic image to the multimodal subsystem.

The six-subsystem architecture has new potential for re-

ordering constituents of representations and for keeping information active over the short term. The earlier architectures merely allowed memory systems to pattern complete information in mental images—and this restricts the possibilities for reordering to “reinsertion” of information within the temporal extent of any image. The presence of a central loop allows more extensive reordering but only in the visuospatial domain. For example, we can think of a to and fro “dialogue” in this loop in which information is sent to the spatial-praxic subsystem that then leads to associated but independent pattern completion in the image of the latter subsystem that is then sent back to the multimodal image, allowing constructions of elements in image content that had never previously co-occurred in sensory experience. Equally, the same information can, in principle, be continually regenerated over and over again, allowing for the first time the potential not only to imagine an action but also to *rehearse* its form internally. This would enable the multimodal and spatial-praxic memory systems to “learn” about repeated patterns of information that had internal rather than external origins.

This architecture also benefits from an additional level of abstraction. All three sensory flows of information to the multimodal subsystem remain in place, but there is now a fourth flow of information arriving from the spatial-praxic subsystem, and this has itself undergone two successive steps: detailed analysis of visual form has led to a spatial-praxic abstraction and, in the second step, regularities underlying this new level of “representation” are passed to the multimodal system—and this captures the abstract organization observed behavior in the world and of the actions needed to coordinate adaptive responses to them. The multimodal subsystem now “sees” new combinations involving a blend of both the first-order derivatives of sensation and some second-order ones, enabling its memory to derive and model some third-order abstractions underlying patterns in information.

An understanding of how executive functions can emerge out of interactions can be illustrated in terms of a “mental dialogue” between the two central subsystems. In each dialogue exchange, information states are updated in the multimodal and spatial-praxic images. “Planning” is not something that is “done by” either of these systems in isolation, but it occurs in their interactions. Imagine a quiz game in which contestants are asked to identify the subject of a photograph that undergoes a succession of steps from a highly pixelated image to a more defined one. At some point, the content of the photo becomes sufficiently defined for someone to answer the question. In much the same way, over successive cycles of dialogue between the spatial-praxic and multimodal subsystems, two interrelated images would stabilize and jointly support the execution of an action sequence that best dovetails with all the constraints of current visual input, sound input, and postural dynamics. Executive functions can be construed as resulting from a dialogue in which no single party has homunculus-like properties: they simply emerge from a collection of constraints. Relative to simpler architectures,

there are *additional* constraints arising from the new level of abstraction, but the control problem of coordinating constraints is no different in kind.

This six-subsystem architecture, we argue, is sufficient to account for the mental capabilities of great apes and, by inference (Byrne 1995), to the last common ancestor shared with modern humans. The spatial-praxic loop is consistent with the ability of some species of great apes to communicate in quite advanced ways using graphical symbols or gestures (Savage-Rumbaugh 1986) and with their use of multiple tools (McGrew 1992), including a basic capability for stone knapping (Toth et al. 1993). Most important, it is consistent with evidence that they are capable of “program-level” imitation (Byrne 2002) that relies on learning the organization of action sequences rather than the copying of detail. The ability to separately “buffer” recent images of abstract visual form and potentially regenerate them via rehearsal is consistent with a recent report of enhanced working memory in chimpanzees for visually presented numerical material (Inoue and Matsuzawa 2007). The ability to see deeper organizations of spatial praxis and to process more sophisticated multimodal contingencies while being able to mentally manipulate both can also be directly related to evidence for some aspects of “theory of mind” in chimpanzees (Tomasello, Call, and Hare 2003). More sophisticated pattern recognition and a grasp of spatial-praxic organization would support not just mental rotation or the control of jumping but also the prediction of quite complex spatial-praxic behaviors of other animates.

### Three Transitions to Modern Thinking in the Hominin Line

The background now in place allows our argument to be extended first into the auditory-verbal domain and then to meaning. Only three reconfigurations can take us from an architecture that can account for the abilities of the last common ancestor to one that can arguably account for modern thought (fig. 3).

For a new “central” subsystem to emerge, our argument holds that there must be two different sources of variation that are correlated in the image of the multimodal subsystem. Having two sources of interrelated variation is a precondition for the extraction of the statistical invariants that underlie both. This implies that the sequence for spatial-praxic abstraction simply replicated in the auditory-verbal domain. The logic of this argument dictates that the next step must have involved the separation of a seventh subsystem specialized to control vocal articulation.

It is well known that great apes lack independent control of breathing and that this restricts their range of vocalization. There is much debate about when flexible speech appeared (e.g., see Davidson 2003; Fitch 2000; MacLarnon and Hewitt 1999). However, once it is achieved, vocal utterances can differentiate. As with dexterity in limb control and manipulation, there would then be two sources of feedback to the multi-



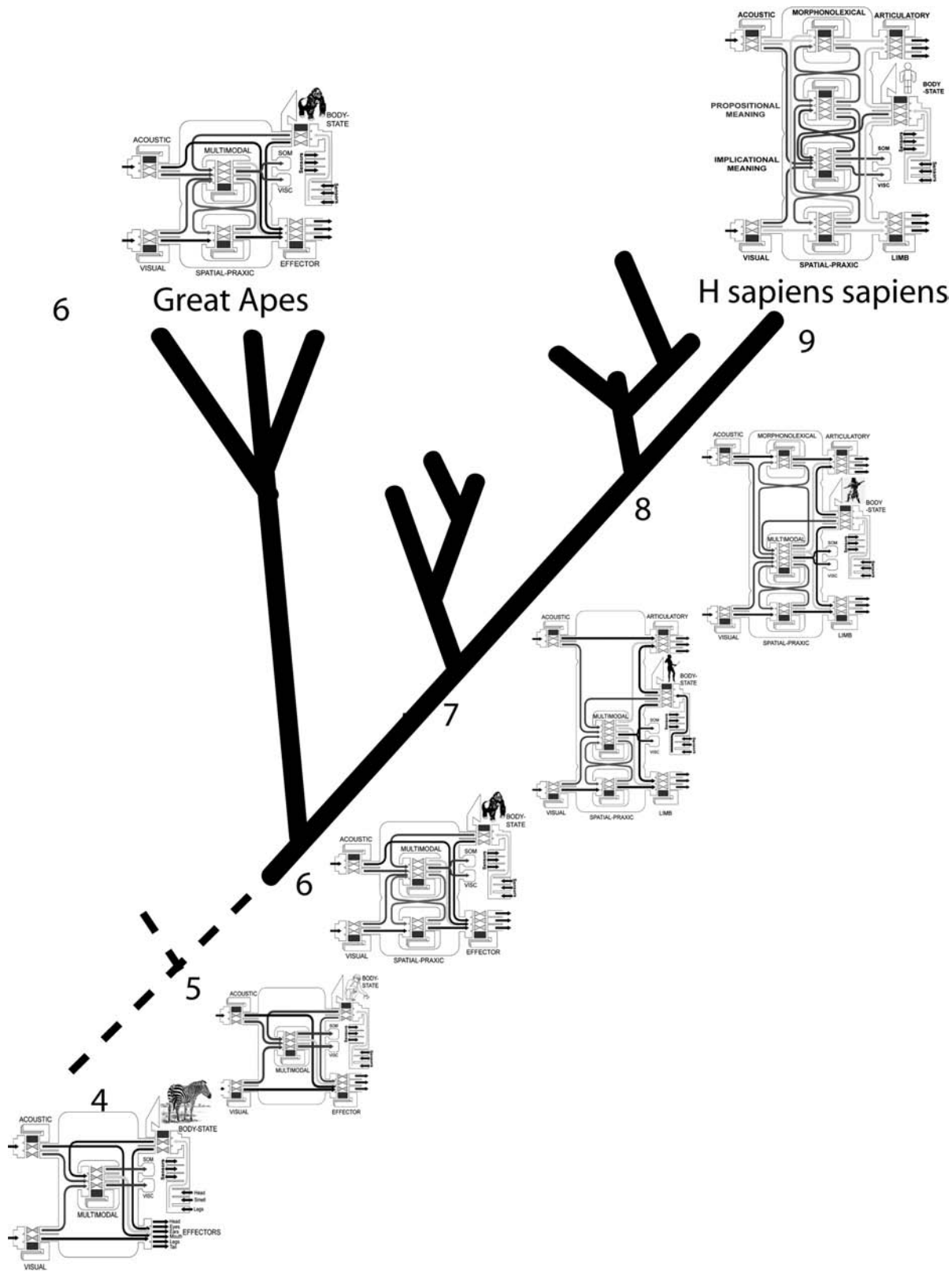


Figure 3. Hypothetical evolutionary trajectory from four to nine sub-systems.

modal subsystem, relating, in this case, to the control over time of breathing and lip and tongue positioning. Bodily feedback concerning that dynamic would be correlated in the multimodal image with the feedback of own speech via the feed from the acoustic subsystem. The invariant patterns underlying both are the phonology and morphology of speech. Once the patterned use of vocal form becomes fully statistically independent of all other multimodal contingencies, an eighth subsystem, the “morphonolexical” subsystem (Barnard 1985), would be in place whose encoding of information would be ordered segmentable “words.” As with the emergence of the sixth subsystem, this would serve a dual function—it would mediate one direct path from heard speech to vocal articulation and enable concurrent interactions with the multimodal subsystem. This eight-subsystem architecture would have the capability for productive verbal imagery as well as productive spatial-praxic imagery (fig. 4).

Mirroring the addition of the fifth subsystem, a seventh subsystem provides an additional image in the mind that can be attended to, but the content of this image is correlated over time only with the speech-based content of acoustic images and hence adds little extra in the way of “cognitive” capabilities. It nevertheless heralds some important consequences for the cultural transmission of behaviors, and these will be discussed in the final section.

The addition of this eighth subsystem would have much greater significance for working-memory capacities. Any owner of this architecture would, via the abstraction of vocal invariants and the compression that encoding brings with it, be able to represent and separately attend to longer segments of speech input and output. As with the emergence of the spatial-praxic subsystem discussed earlier, they would have been able to reorder elements of vocal streams, be they heard or spoken, and extract deeper organizations of verbal patterns. Assuming some arbitrariness in what sounds went with what, any patterning or “rules” of combination would depend largely on cultural factors rather than the physics underlying spatial praxis. An eight-subsystem architecture would have had a productive form of vocal communication with systematic structure and far greater expressive possibilities than the seven-subsystem architecture. The addition of an eighth subsystem enables pattern completion at a “morphonolexical” level and, via the newly enabled dialogue with the multimodal subsystem, the ability to imagine, rehearse, and react physically and emotionally to what might be said either by themselves or by others, with consequential extensions of theory of mind and predictions concerning social interaction. In an eight-subsystem architecture, there are internal representations of spatial praxis, of multimodal abstractions, and of morphonolexical representations. This gives rise to greater demands on “executive functions” for directing attention internally and resolving what processes do. Executive functions would now emerge out of “a three-party conversation” involving two concurrently active loops rather than the single central loop of earlier architectures. While this might require

more sophisticated models for a “communications protocol,” there is no reason to suppose that it required any fundamental changes to the mechanisms for resolving multiple constraints that were present in the four-subsystem architecture.

Crucially, productive vocal communication can be intersected with spatial-praxic productivity as a consequence of the two internal feedback loops into the multimodal image. Indeed, this architecture now has substantial overlap with the classic working-memory model in which a central executive controls both a phonological loop and a visuospatial scratch pad (fig. 5). The additional processing pathways mean that any hominin with this architecture, in principle, could have understood a “rule-derived” and quite complex verbal instruction *while* knapping stone or could have issued quite complex verbal guidance to another in its band.

The eighth subsystem would not have brought any deeper abstractions than were present in the far earlier six-subsystem architecture. The inputs to the multimodal subsystem still either arrive directly as first-order derivatives of sensation or via two stages of processing in the verbal or spatial-praxic domains. According to the argument being pursued here, the presence of the eighth subsystem creates exactly those conditions required for the subsequent emergence of a deeper level of abstraction. There are now two sources of complex and correlated variation. Hominins with this architecture would have been “talking about” objects, animate agents, and environments, as well as about the *organization* of events and actions involving these entities in interrelationships over time. The abstract organization of both seen and heard events and internally created representations of them are now both fed back into the image of the multimodal subsystem as second-order abstractions. In order to support a wider range of behavior, the multimodal subsystem would need to assign more and more capacity to third-order abstractions capturing what goes with what in the combinatorial explosion of intersections between vocal and praxic forms.

What verbal and spatial-praxic modalities of expression have in common is reference to the identities and properties of entities and the relationships they enter into in happenings in the world, be they physical or social in nature. Invariants of this kind are what we would conventionally refer to as “propositional” semantics. Important subsets of actions would, for example, always have an agent involved in creating changes of state, and some of those changes would require an object or collection of objects with particular properties (e.g., hardness or numerosity). Hominins with eight subsystems would be both performing and talking about actions such as breaking a mass of food into smaller portions manually or with the aid of a tool or cutting up or fragmenting material such as stone or wood, and they may even have talked about dividing agents in the band into subsets for achieving different tasks in foraging. The invariants underlying these examples are “partition” of object(s) by an agent with the optional use of an instrument, and these are distinct roles in semantic case grammars (Fillmore 1968). Whereas multi-

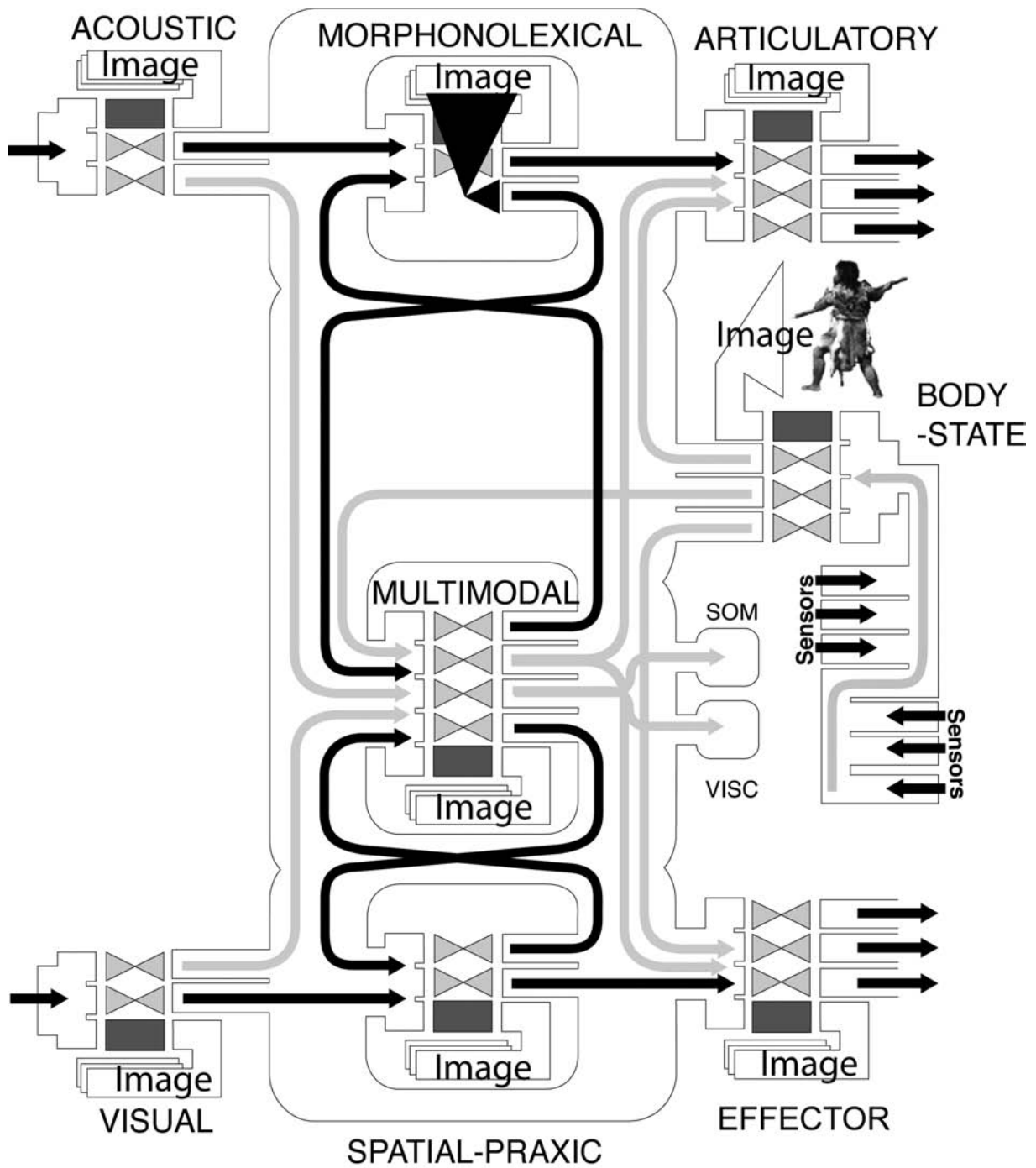


Figure 4. Eight-subsystem architecture (modified from Barnard et al. 2007).

modal components in seven-subsystem architectures would be able to make distinctions guiding very similar overt actions, only the multimodal subsystem of an eight-subsystem architecture would have the capability to extract what complex verbal sequences and happenings in the world have in common. Unlike all previous architectures, the eight-subsystem

one provides a platform within which a system of referentially specific meaning can evolve as third-order abstractions. Once a significant fraction become statistically independent of all other multimodal invariants—such as the emotions attaching to objects, events, or happenings—a ninth subsystem specialized to process specifically propositional meanings would

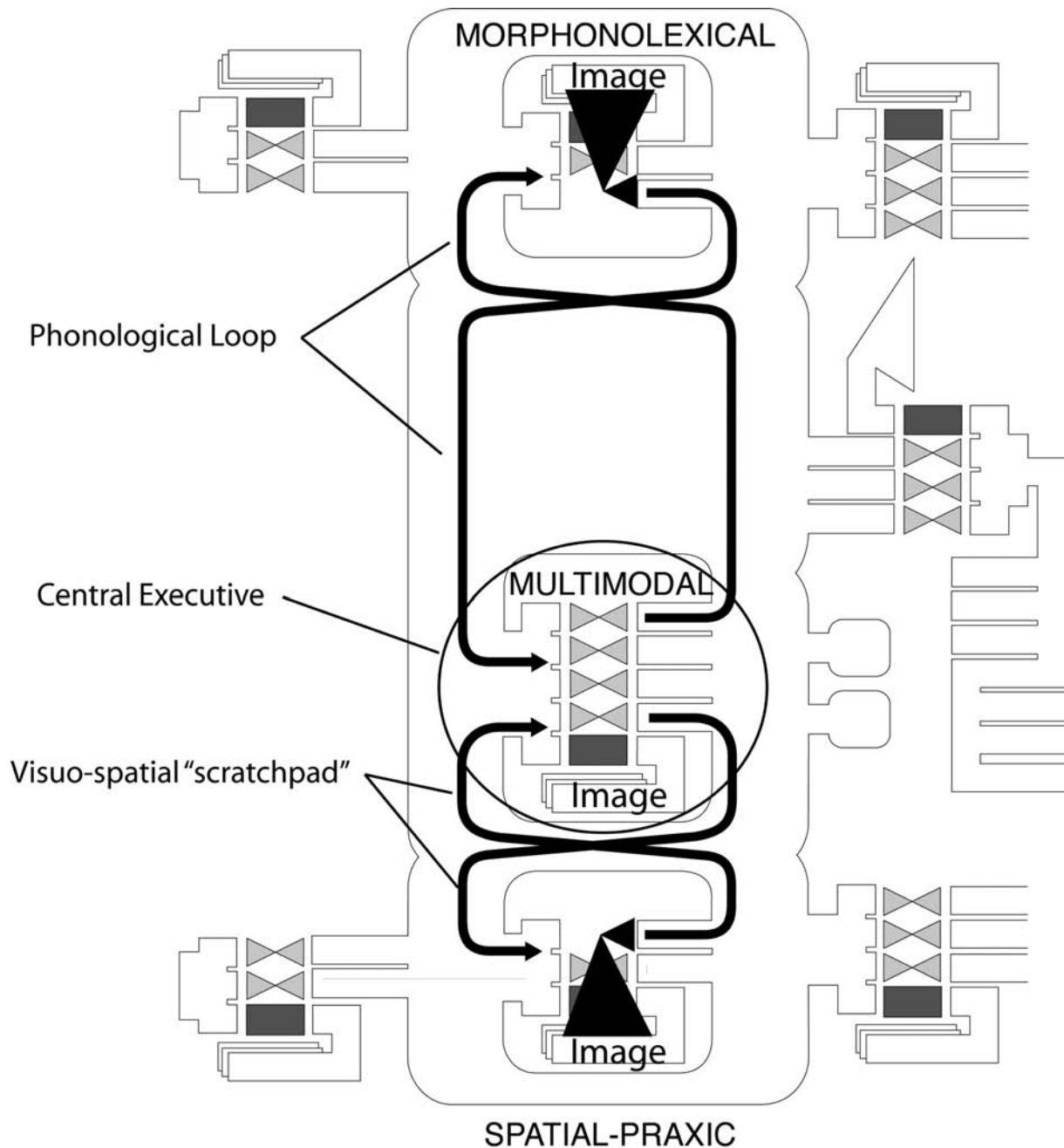


Figure 5. Isomorphism between an eight-subsystem architecture and the classic working-memory model (Baddeley 1986).

emerge, and it is this final step that is seen as supporting fully modern thinking (fig. 6). The resulting nine-subsystem mental architecture devolves control of action and speech to peripheral mechanisms while allowing the new central subsystems to focus their attention on decision making based on abstract meanings.

This last architecture involves several step changes in working-memory capacity. The new form of meaning carved out

of the multimodal capabilities of the eight-subsystem architecture is propositional semantics, and this now lacks the potential for emotional charge. The nine-subsystem architecture is, in principle, capable of talking about emotional states without necessarily experiencing them. Material still arrives at the multimodal subsystem, relabeled the “implicational” subsystem (following Barnard 1985), directly from the three sensory subsystems, and emotional charge is retained at this

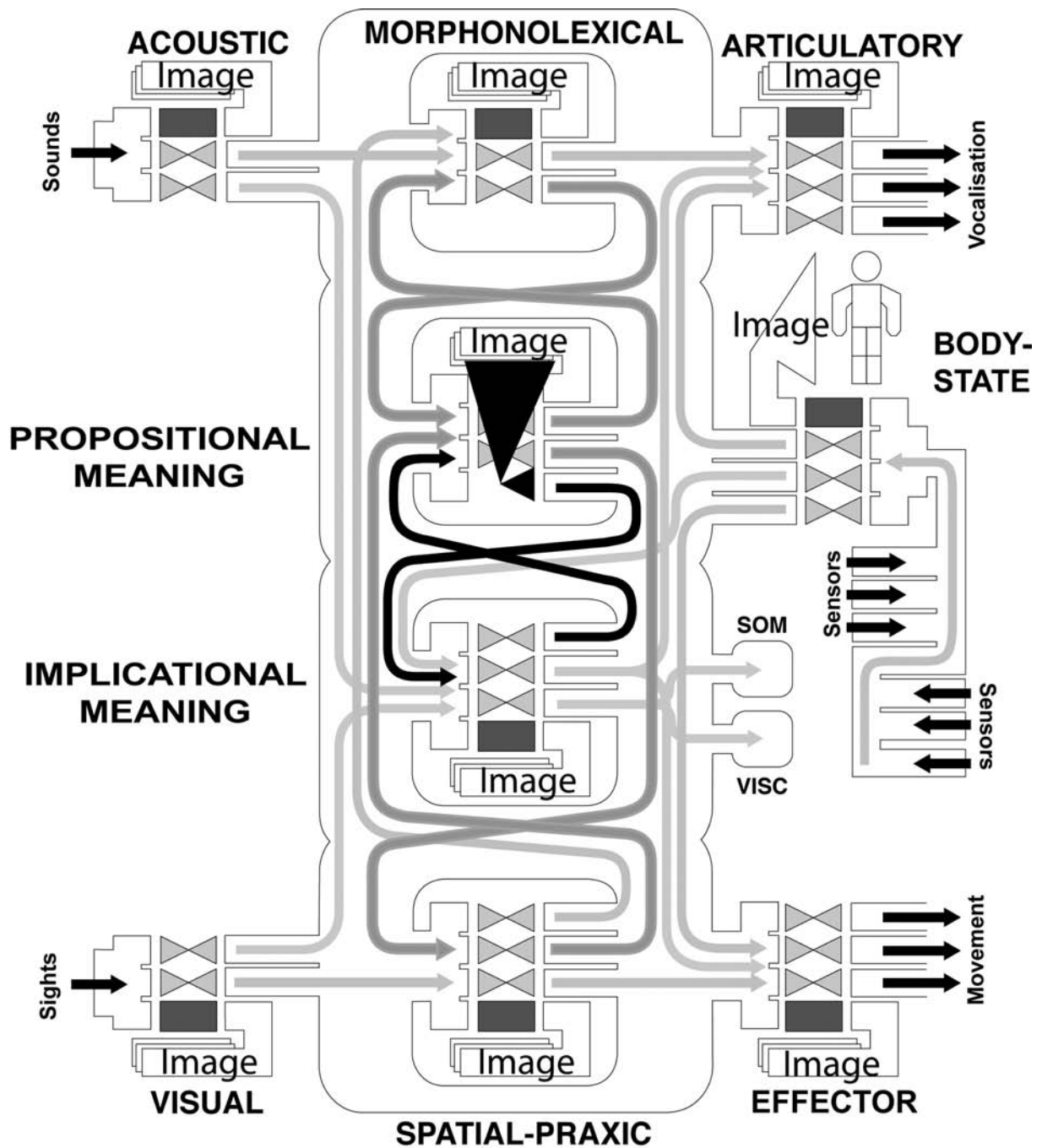


Figure 6. Nine-subsystem architecture proposed by Barnard and Teasdale (1991).

level. The other material sent to the implicational subsystem now arrives from the propositional subsystem, and what is sent is an abstraction over specific propositions rather than over verbal form.

The implicational subsystem has unique properties when compared with all its multimodal precursors. Its memory system is in a position to extract and model some new fourth-

order dependences over the third-order meanings processed at a propositional level—metarepresentations of meanings—and blend those with the more immediate derivatives of sensory states. These meanings are deeply “schematic,” and we have referred to them elsewhere as “schematic models of self, world and others.” Their information content can be equated with generic feelings or felt senses of intuition/wisdom (for

detail, see Teasdale and Barnard 1993:66–76). The propositional subsystem also has a unique characteristic—all of its inputs originate from other central subsystems. It receives no information that is necessarily constrained by first-order derivatives of current states of the world or body.

This architecture has a new central loop (fig. 6, *black shading*), allowing information to be exchanged between the two meaning subsystems. Whereas all the precursor architectures required processes in their multimodal subsystems to control the *form* of verbal or spatial-praxic responses and imagery, these roles are now assigned to processes in the propositional subsystem. These manage information exchanges in this model's analogues of the visuospatial scratch pad and the phonological loop. The dialogue between the two meaning subsystems can occur at the same time as more peripheral resources manage the details of controlling speech and actions and any internal imagery associated with them. Just as the six-subsystem architecture allowed the reordering of elements of spatial praxis and the eight-subsystem architecture allowed the reordering of auditory-verbal forms, the nine-subsystem architecture adds a capability to reorder elements of “ideas.” Hence, the current system-level approach associates the ability to reorganize/recursively combine components of mental representations with the successive emergence of these three central processing loops. With each new loop, specific new capabilities for hierarchical and sequential reorganization emerge first in the control of spatial praxis (including gestures), then in verbal communication, and finally in abstract thought.

The nine-subsystem architecture has the capability not just to make a tool or talk to another member of its band. Its additional central processing “loop” could, in theory, enable it to think about how to make a better tool (conceptual planning) or about what others might be thinking about it (full theory of mind), or it could enable it to be concerned about whether its out-of-sight offspring might be in danger (caring for others), or about how many shellfish its partner might have collected for lunch (algorithmic), or about how to depict bison on a cave wall (aesthetic sense). Unlike all precursor architectures, this new central loop would support productivity and learning not only in the spatial-praxic and auditory-verbal domains but also in the mental domains of ideas about self and others, as well as physical and metaphysical worlds. In the nine-subsystem architecture, executive functions would now need to evaluate whether an idea that crystallizes in the mind is worth thinking about rather than just constraining whether something is worth saying or doing.

There is still no requirement for a homunculus-like executive. The functions of decision making or planning or directing attention emerge, as before, out of exchanges of information between different levels of representation and the constraints they collectively bring. The executive control mechanisms determining whether to initiate action at that point or to think more about the properties of an idea would

be an integral component of what was modeled in the meaning systems and successive exchanges between them.

Executive control involving meaning is not “deterministic.” For example, attention can be directed internally to only one of now four “central” images, as well as to sensory images, although what is attended to can shift moment to moment. This means that attention can be directed at the meaning of propositions (the buffered process in fig. 6 is using propositional meanings) or to implicational meanings. When asked the question “How many animals of each kind did Moses take into the ark?” experiments have shown that most undergraduates answer “two,” not noticing that the biblical agent was really Noah (Erickson and Mattson 1981). They do not fall into this trap when asked “How many animals of each kind did Nixon take into the ark?” Because Moses and Noah are very similar (male Old Testament figures and benefactors), they would fit the same generic schema in online implicational processing, allowing the false presupposition to pass unnoticed. Nixon fits a different pattern (male U.S. president and devious), and a mismatch in implicational patterning of what usually goes with what would stand out like a sore thumb. The presence of a discrepancy is itself sufficient to redirect attention away from propositional content and to implicational image content that might provide alternative schema for what might have been meant, with successive exchanges and attention shifts between the two levels of meaning trying to resolve how to answer the Nixon question. More or less “rational” or more or less “impulsive” responses can emerge simply as a function of the level of meaning to which attention is directed, and such patterns may move to extremes in psychopathologies, such as depression or mania (Barnard 2004). Control of mental processing activity by attributes of two levels of meaning would have been impossible in eight-subsystem architectures.

## Mapping Mental Architecture onto the Archaeological Record

Our proposals share many implications for understanding archaeological evidence with other analyses of the evolution of language, meaning systems, and tool use (e.g., see Christiansen and Kirby 2003; Deacon 1997; Gibson and Ingold 1993; Noble and Davidson 1996). There are also differences. The emphasis here on a sequence of well-specified architectures brings into focus the idea that evolution enabled minds with more advanced architectures to do more things at the same time. By the very nature of the sequence, our proposals inherently provide tight couplings between the evolution of cognitive processes, language, meaning, and more refined emotions (Barnard et al. 2007). The system-level account directs our attention away from evidence pinpointing the emergence of particular capabilities such as the use of iconic, indexical, and symbolic representations (Rossano 2010, in this issue) and more toward asking questions about the “whole package” of theoretically derived capabilities that come with

a mind organized in a particular way. How do the respective properties of seven-, eight-, and nine-subsystem “packages” described above best fit the overall patterning of evidence? For example, is the best fit to assign the emergence of a seven-subsystem architecture to *Homo erectus*, an eight-subsystem architecture to archaic species of *Homo*, and a nine-subsystem architecture only to *Homo sapiens sapiens*? Tool use and brain size provide two sources of evidence that provisionally converge on that assignment.

Empirically grounded work on the relationship between brain size and grooming, a social behavior linked to positive affect, has been used to suggest that vocalization served a social function for *H. erectus* (Aiello and Dunbar 1993). In addition to this argument, we can suggest further hypothetical properties of the communication system that would be available with a seven-subsystem architecture. Its articulatory code would support vocal imitation and the potential for mimicking sounds made by other animates, natural phenomena such as a rushing stream, and even sounds made during tool manufacture. A flexible code would also enable novel combinations of articulatory elements to occur bearing only arbitrary relationships to what they signified in the absence of a sophisticated meaning system. This capability suggests that the appearance of Acheulean tools need not have been a consequence of advances in manual or spatial skill (Wynn 1989, 2002), allied in our analysis to the far earlier emergence of a six-subsystem architecture. The guidance of vocalization and a significant capability to blend positive and negative affect with vocal patterns that are not innately endowed could have facilitated multimodal instruction and the cultural transmission of skills over generations in a way that would have been beyond the reach of species with a mental architecture lacking flexible articulation.

This assignment would still be consistent with a long period of stasis in the record of tool manufacture. The seven-subsystem arrangement lacks a capability for reordering larger segments of utterances and requires central control of vocal output, properties that effectively place an upper limit on what could be accomplished communicatively. Both guidance of tool manufacture by vocalization and vocalization subserving other social functions would have cumulatively led, in the normal course of natural selection, to an increased range of utterances. Neither need be assigned greater evolutionary significance than the other. Differentiation in both domains would simply have helped create the conditions required for an eighth subsystem to emerge.

The properties of an eight-subsystem architecture provide a platform on which yet more sophisticated systems of communication and instruction could develop cumulatively over time: longer utterances, via the compression of auditory material into a more abstract “morphonolexical” representation; the reordering of verbal elements; and the ability to retrieve and mentally manipulate verbal representations while acting in the world. Based around a grasp of the organization of spatial praxis at an equivalent level of abstraction, this form

of communication would, in principle, facilitate both the emergence and the subsequent cultural transmission of deeper underlying organizations of skilled actions and social behaviors. Recent analyses of lithic reduction sequences, including Levallois flakes (Moore 2010; Wynn and Coolidge 2010), and of the Schoenigen spears (Haidle 2010, in this issue) provide good evidence for more elaborate organizations underlying tool manufacture and use across archaic species of *Homo*. As with the seven-subsystem architecture, there are also derivable limitations on what can be accomplished within an eight-subsystem architecture. Its “working-memory capacity” would have been entirely occupied by generating actions in the world or by understanding and producing verbal utterances.

The multimodal image of an eight-subsystem architecture could well have marked out feeling “good” or “threatened” across a range of related auditory-verbal, spatial-praxic, and social settings and could have used that information in generating speech forms and actions. The architecture would still be incapable of generating a fully abstract concept as to why they or others felt or acted that way across related settings or to think systematically about how to make a better tool or how to negotiate more effectively in social networks. Meaning is, in a very real but restricted sense, “implicit in” the capabilities of the multimodal subsystem of this architecture. Within its working-memory capacity, it can “see” the deep structure of correlations between what is seen, heard, and felt in the body (see Barnard et al. 2007; Byrne et al. 2004). Were attention to be focused at the multimodal representation of this architecture, affect and “protoconceptual” categories would remain intertwined, with emotional responsiveness lacking “cognitive” refinement—an attribute that can readily be related to the idea that Neanderthals or other archaic species may have lacked sophisticated theory of mind or diplomatic skills (Ambrose 2010, in this issue).

Fully modern thinking, linked to a nine-subsystem architecture, is hypothesized to rely on a collection of properties that come with a distributed multiprocessor architecture for “working memory.” Thought is seen as a conjoint function of the emergence of propositional meaning, the presence in implicational meanings of fourth-order abstractions (thinking in terms of wisdom/intuitions/feelings rather than cold facts), and the new exchanges that can go on between these two levels of meaning while talking and acting in the world. The appearance of art and personal ornamentation and the use of mineral pigments are all traditionally associated with the emergence of symbolic representation. In our proposals, they would be “explained by” the presence of two interacting levels of meaning, with one representing referential content and the other a blend of intellectual and affective significance.

The extraordinary differentiation of tool types characteristic of the upper Paleolithic at least in part can be thought of as mediated by the additional loop between these two levels of meaning. As noted earlier, a nine-subsystem architecture could think about how to fashion a different and better tool

while knapping and talking or could imagine how tools of different forms could achieve different ends (see also Beaman 2010, in this issue). Only an architecture capable of extracting some fourth-order regularities could generate truly abstract ideas in self-reflective thought—such as construing the self as an entity that generally “succeeds” or is “persecuted” by others. Such generalizations require the capability to extract regularities underlying variations in propositional form, and the presence of such abstractions, along with their productive expression in language, would seem to be essential for the development of the most advanced forms of teaching, beliefs, and the cultural transmission of abstract ideas.

While fully fledged art may well have appeared only late in the record, evidence linked to tool manufacture can be interpreted as indicative of conceptual abstraction at earlier dates without requiring reference to “symbolism.” As a case in point, Wadley (2010, in this issue) discusses the evidence of compound adhesives used in hafting found at Sibudu in southern Africa from 70 kya. The procedures revealed through reconstructive work were manifestly intricate, involving highly disparate ingredients, a significant variety of alternative recipes, and carefully controlled management of drying and heating. Any “errors” in the chain would have been costly in terms of wasted time and lethal risk at the time of weapon use. The level of variation in ingredients, recipes, and temporal extension of subprocedure in manufacture is important. It implies a multiplicity of mappings from concrete cues to outcomes. In this context, use of multiple procedures and subprocedures and their adjustment for subtle differences in available ingredients would likely pose a challenge for simple mechanisms of learning or generalization based on chaining subprocedures that rely on purely physical similarities among alternative ingredients.

These adhesive makers would almost certainly have benefited from grasping abstractions over the elements and outcomes of different subprocedures, such as viscosity and consistency, to achieve reliable results on realistic time allocations in both acquisition of the skill and its day-to-day use. It is hard to imagine how this could be achieved and culturally transmitted through gestural demonstration alone without the supplementation of verbal instruction that referred *both* to the deeper organization of action sequences *and* to abstract properties of substances. If so, use of varied compound adhesives would constitute evidence for the presence of a nine-subsystem architecture. By contrast, evidence of adhesive use in Neanderthal hafting is limited to noncompound materials such as bitumen (e.g., Boeda et al. 1996) and hence far fewer requirements for the cognitive management of material variation. This would be entirely consistent with the restrictions of a system of communication supported by an eight-subsystem architecture lacking propositional abstraction. Bridging evidence that compound adhesives necessarily required abstraction (Botha 2001) is currently lacking but could be sought in future reconstructive work by instructing novices with and without the support conceptual abstractions.

Whether increases in cranial capacity were continuous or discontinuous remains controversial (e.g., Henneberg and de Miguel 2004). In spite of this, it provides some convergent evidence concerning the time frames for the emergence of seven-, eight-, and nine-subsystem architectures. It is important to emphasize that differentiation can occur over generations of one or more species with the same mental architecture. Increases in brain size across the era of *H. erectus* are modest, consistent with increasing differentiation limited to the articulatory domain. The earliest eight-subsystem architecture may well have been implemented in brains of modest physical size, comparable to those of its seven-subsystem precursors. In our proposed trajectory, underlying neural architecture, cognitive architecture, and the behavioral repertoires they support would all coevolve in small steps. An “early” eight-subsystem architecture could well have enabled abstraction of a modest range of multimodal contingencies that nonetheless support a full behavioral repertoire for foraging, tool making, or social interaction. Selective pressures would have increased the chances of survival for those capable of a larger repertoire of adaptive behaviors and with the underlying neural capacity required to achieve it. This would be consistent with more dramatic increases in brain size and perhaps subtle alterations in morphology (Bruner 2010, in this issue) occurring across archaic species of *Homo* as more intricate multimodal processing underwent adaptive differentiation within an eight-subsystem architecture.

Successive increases in behavioral repertoire and brain size would be required to arrive at a point where there was sufficient correlated variation in the images constructed to create the conditions in which a new daughter subsystem can emerge. This provides some theoretical motivation for increases in cranial capacity being associated with periods in which the capabilities of a new architecture are exploited and developed rather than the emergence of new “cognitive” functionality itself. Following a reorganization of processes with more compact coding systems, more can be accomplished within the same brain capacity, perhaps even allowing subsequent metabolic economies through contraction with no loss of cognitive capability. Modern humans would be able to do far more with a cranial capacity comparable to or even smaller than that of *Homo neanderthalensis*. The existence of *Homo floresiensis*, with a brain size comparable to that of chimpanzees (Falk et al. 2005) but with tool-making capabilities at least as sophisticated as those of the larger-brained *H. erectus*, would also be consistent with an architecture-dependent analysis linking brain size to cognitive capabilities.

The architecture-dependent analysis offered here also brings into perhaps sharper focus questions that need to be addressed in debates concerning the interpretation of evidence for differential expansion of specific brain regions across evolution (e.g., see Schenker, Desgouttes, and Semendeferi 2005; Semendeferi and Damasio 2000). First, the separation of one subsystem into two involves a reassignment of previously integrated neural circuitry. It would seem sensible to hypoth-



erize that the daughter subsystem is initially the smaller fraction of its precursor parent, because that would involve carving out fewer circuits. Second, the effects of new mental functionality must necessarily propagate capacity demands across the wider neural system. The emergence of flexible vocalization (seven subsystems) or reorderable verbal communication (eight subsystems) will also increase demands for auditory analysis and demands for multimodal synthesis, as well as enable new spatial-praxic activities that in turn benefit from more refined motor control. In this view, an  $n$ -generation eight-subsystem brain could well bear a far closer resemblance to the brain of a nine-subsystem architecture than it does to a first-generation eight-subsystem brain. This analysis suggests that any differences in relative volume or connectivity could again be linked to the extent to which new mental capabilities have been exploited rather than to their initial emergence.

In conclusion, the arguments presented here are based on the specification of a hypothetical series of mental architectures linked to a single mechanism of process differentiation. Mappings of this analysis to the archaeological record exhibit rather more speculative content than is ideal. However, it is hoped that the technical approach adds options for interpretation that can be further refined, tested, and assessed against alternative positions as additional evidence is uncovered in the future.

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# The Phonological Loop

## A Key Innovation in Human Evolution

by **Francisco Aboitiz, Sebastián Aboitiz, and Ricardo R. García**

The phonological loop—here referred to as a specialized auditory-vocal sensorimotor circuit connecting posterior temporal areas with the inferior parietal lobe (Brodmann’s areas 40 and 39) and the ventrolateral prefrontal cortex (Broca’s region, Brodmann’s areas 44 and 45)—is proposed to have been a fundamental element associated with the origin of vocal language in human evolution. This circuit derives from auditory prefrontal networks that preexist in the nonhuman primate but that acquired an unprecedented development in the human brain. The phonological loop overlaps and possibly coevolved with a more ancient circuit involved in hand manipulation and gesture coding (the parieto-frontal mirror neuron network) and is complementary to a “ventral” auditory circuit connecting the anterior temporal region with anterior Broca’s area (area 45) via the extreme capsule. The development of the phonological loop produced a significant increase in short-term memory capacity for voluntary vocalizations, which facilitated learning of complex utterances that allowed the establishment of stronger social bonds and facilitated the communication of increasingly complex messages, eventually entailing external meaning and generating a syntactically ordered language. Furthermore, this circuit served as a template for the generation of more elaborate networks supporting these new modes of communication. Finally, the increase in short-term memory capacities associated with the elaboration of such networks facilitated the generation and processing of recursive linguistic structures based on long-distance dependencies between linguistic elements and on syntactic movement of phrase constituents. Thus, the acquisition of a functional phonological circuit can be considered as a key innovation that made possible a series of subsequent changes in human evolution leading to the complex and recursion-based language of modern humans.

Language is uniquely human. As a species-specific character, it is expected to have a genetic component; that is, there might be innately generated mechanisms underlying our modes of communication. Although very few would argue against these statements, there is considerable controversy regarding the specific features of language that are innate and species specific and those that relate to general cognitive processes that can be found in other species. Some scholars (Fitch, Hauser, and Chomsky 2005; Hauser, Chomsky, and Fitch 2002), on the basis of the imperant structuralist perspective led by Noam Chomsky, claim that language contains several elements partly shared with other species, such as perceptual and motor ca-

pacities that permit us to generate and process complex stimuli, including speech (categorical perception, detection of transitional probabilities, perception of rhythm, etc.; see Mehler et al. 2006; Yip 2006), but there are some key elements that are unique to our species. Among these, the ability for linguistic recursion (briefly, the capacity to generate nested utterances by inserting sentences into sentences ad infinitum) stands out as being uniquely human.

A different point of view claims that language can be seen as a biological adaptation showing species-specific features at all levels: phonological, syntactical, lexical, and semantic (Jackendoff and Pinker 2005; Pinker 1995; Pinker and Jackendoff 2005). This view claims that the structuralist perspective referred to above profoundly neglects the biological basis of linguistic processes and the fact that we humans are the result of the process of Darwinian evolution. Still other proposals claim that language emerges from the elaboration of preexisting cognitive elements in an expanded brain and that the resulting structural complexity of language is a consequence of constraints imposed by our cognitive architecture (Langacker 2000).

**Francisco Aboitiz** is Professor in the Departamento de Psiquiatría y Centro de Investigaciones Médicas, Escuela de Medicina, Pontificia Universidad Católica de Chile (Marcoleta Avenue 391, Santiago, Chile [faboitiz@puc.cl]). **Sebastián Aboitiz** is an undergraduate student in the Facultad de Ciencias Sociales, Pontificia Universidad Católica de Chile (Santiago, Chile). **Ricardo R. García** is Professor in the Centro de Estudios Cognitivos, Facultad de Filosofía y Humanidades, Universidad de Chile (Santiago, Chile).

Research on the genetic basis of human language, however, has not produced clear-cut results that permit the discrimination of these different approaches. There is evidence for strong selection of a few genes in the human lineage, some of them being expressed in the brain (Fisher and Marcus 2006). However, most of these may have more to do with increasing brain size than with specific aspects of language. Expectations were raised with the discovery of a mutation in the gene FOXP2 in affected individuals of a family that carries a familial speech disorder. However, instead of clarifying the issue, the current interpretation of FOXP2 function is highly controversial, as exponents of every linguistic interpretation claim that the role of this gene in language supports their own view (Marcus and Rabagliati 2006). Perhaps the most parsimonious conclusion in this context is that “language is a complex reconfiguration of ancestral systems, adapted in evolutionary novel ways” (Fisher and Marcus 2006:9). This conclusion is comparable to an early proposal that few genes would have been subject to selection during human brain evolution—mainly those involved in increasing neuronal proliferation and brain size, with an important role in the mechanisms of selective synapse stabilization in shaping new neural circuits (Aboitiz 1988). Nevertheless, it was acknowledged that some subtle genetic changes affecting the dynamics of these stabilization processes, or the relative preference of certain axons for different targets, might have also played a role in determining specific circuits, such as those involved in language processing in the left hemisphere.

In this article, we will address the origin of human language from a neurobiological and evolutionary perspective by considering that the capacity for language requires a sufficiently large brain but that this might not be sufficient. In this context, we will propose that there was a key innovation in the human lineage that propelled the evolution of language and the selection of linguistically more apt brains. This key innovation is claimed to be the development of a phonological loop (by this we understand a specialized auditory-vocal circuit for phonological processing) that arose in the context of a powerful phonological (and gestural) imitative mechanism in early hominids, possibly supporting mother-child interactions (Aboitiz and Schröter 2004; Aboitiz et al. 2005; Falk 2004). This character endowed early humans with elaborate abilities to recognize kin and to signal basic meanings, which were probably important elements in the establishment of social bonds and of high selective value. Together with the acquisition of more elaborate utterances, true words and increasingly complex meanings appeared, and eventually a syntactically ordered language arose, possibly in the context of complex tool making and more extended social exchanges (see Ambrose 2010, in this issue). Possibly, there were many different kinds of protolanguages; however, only one of these survived in the same way that there was a diversification of early hominids but only one species is extant today. One possibility is that our language differed from the other alternative protolanguages in the ability to generate recursive syn-

tax (although this possibility will be obviously very difficult to verify). The present proposal is based on earlier reports in which we have proposed the existence of circuits partly homologous to the language circuits in the nonhuman primate (Aboitiz 1995; Aboitiz and García 1997, 2009) and a role for short-term memory mechanisms in language origins (Aboitiz et al. 2006*a*, 2006*b*).

In this article we will first introduce the concepts of working memory, our interpretation of the phonological loop, and their neural correlates, and then we will attempt to make a link between phonological acquisition and the development of syntax and recursion from an evolutionary perspective. As mentioned, our main point here is that the phonological loop represents a fundamental evolutionary innovation that made possible the origin of modern humans and modern language.

## Working Memory and the Phonological Loop

Although the concept of short-term memory is not new and seems firmly accepted today, its history in psychology has been controversial. James (1890) distinguished primary memory from the more durable secondary memory, a view that was revived by Hebb (1949), who coined the concept of short-term memory, a process dependent on temporary neuronal activity and different from long-term memory, based on neurochemical changes. Subsequent work, including the reports by Milner (1966) and Baddeley and Warrington (1970) on subjects with bilateral middle temporal lobe damage, served to establish short-term memory as a specific memory form. One characteristic of short-term memory was its rapid decay, which could be prevented by subvocal rehearsal in the case of linguistic tasks (Brown 1958; Peterson and Peterson 1959). Baddeley and Hitch (1974) emphasized this rehearsal mechanism and proposed what they called a multicomponent working-memory model to account for a kind of memory that requires rehearsal to be maintained online and that, contrary to other forms of short-term memory, involves attentional control and the manipulation of information being transiently held. These authors separated a central executive system for attentional control, object manipulation, and “slave” sensorimotor systems that maintained information online through rehearsal. These were the visual-spatial sketch pad, a system that maintains visual-spatial information online and for which rehearsal could be detected by eye movements, and the phonological loop, a transient store of phonological input that could be rehearsed subvocally. Subsequently, Baddeley (2000) added a fourth component, the episodic buffer.

Baddeley (1966) distinguished two components of the phonological loop: a phonological store, which was tapped by the phonological similarity effect (in which subjects less accurately recall sequences of phonologically similar letters or words; Conrad and Hull 1964), and an articulatory rehearsal system, which was evidenced by the word length effect, in which the immediate memory for word sequences decays as words be-

come longer (Baddeley, Thomson, and Buchanan 1975). Thus, there would be a fading trace maintained transiently in the phonological store that could be reactivated by igniting the articulatory mechanism. The mechanisms of decay of this memory trace are not clear yet, but an important element in this process seems to be the existence of competing stimuli that interfere with the trace or act as distractors (see Lewis, Vasishth, and Van Dyke 2006; see also Barnard 2010; Beaman 2010; Engle 2010, all in this issue). In this way, motor rehearsal maintains the network sufficiently activated to resist interfering elements. The rehearsal process could be blocked by articulatory suppression, which consists of articulating an irrelevant sound during the memory task. Baddeley speculated that the phonological loop had a primary role in the acquisition of novel phonological sequences during language learning by children. This proposal was supported by a series of articles indicating an inverse relation in vocabulary acquisition and performance in verbal working memory (Baddeley 1993; Papagno and Vallar 1992, 1995). The causal effect of verbal working memory over language acquisition was strongly suggested by a cross-lagged correlation study, where performance in nonword repetition (which probes the ability to learn new phonological sequences) at age 4 predicts vocabulary at age 5 better than vocabulary at age 4 predicts performance in nonword repetition at age 5 (Baddeley, Papagno, and Vallar 1988).

## Anatomical Evidence for the Phonological Loop

Several imaging studies confirmed the existence of an anatomically restricted circuit that could be ascribed to the phonological loop, including a transient storage component located in the inferior parietal lobe and a rehearsal component involving Broca's area (Brodmann's areas 44 and 45—some authors include area 47 as well; see reviews in Aboitiz and García 1997; Baddeley 2003; Smith and Jonides 1998; see fig. 1). Nevertheless, the exact inferior parietal area that became activated in phonological storage tasks strongly depended on the experimental paradigm, some studies finding activity in anterior regions (the supramarginal gyrus, area 40) and others in more posterior regions, reaching the angular gyrus (area 39) or the posterior parietal lobe (Becker, MacAndrew, and Fiez 1999; Buchsbaum and D'Esposito 2008). Furthermore, studies including passive listening (which by definition should activate the phonological store) and more specific short-term memory such as the delayed-match-to-sample paradigm (see below), evidenced activation in the auditory areas of the superior temporal lobe and in a region termed the superior planum temporale (SPT) in the temporo-parietal junction, which was argued to represent a sensory-motor interface for phonological processing (see Buchsbaum and D'Esposito 2008; Hickok and Poeppel 2007). This evidence was in agreement with lesion sites in patients with predominantly short-term verbal memory deficits. Overall, this evidence indicates

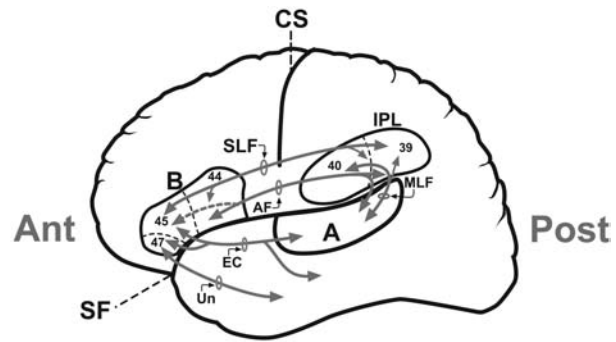


Figure 1. Simplified diagram depicting the language regions of the human brain and their connections, based on tractography techniques. Auditory areas (A) send a dual projection to Broca's area (B; areas 44, 45, and 47) via dorsal and ventral streams. The dorsal stream (i) connects directly posterior auditory areas with Broca's region (especially area 44) via the arcuate fasciculus (AF) and (ii) contains an indirect projection that relays in the inferior parietal lobe (IPL; areas 40 and 39). The latter consists of two pathways, one from auditory regions to the IPL via the middle longitudinal fasciculus (MLF) and the other between the IPL and Broca's region via the superior longitudinal fasciculus (SLF). The ventral stream runs mainly through the extreme capsule (EC) and connects anterior auditory regions with anterior Broca's area (areas 47 and 45). Some authors claim that there are also projections to Broca's region via the uncinatus fasciculus (Un). CS, central sulcus; SF, sylvian fissure. (Anwander et al. 2007; Catani and ffytche 2005; Frey et al. 2008.)

that the phonological store—and in general, the phonological loop—is rather embedded in a sensorimotor circuit that encompasses auditory regions, the inferior parietal lobe, and Broca's area and integrates phonological processing and motor output. This view is consistent with Jacquemot and Scott's (2006) model, indicating a reciprocal interaction between the input and the output phonological buffers. The precise role of the inferior parietal lobe in this process is still controversial, but there is robust anatomical evidence supporting its participation in auditory-vocal processing (see below). Some studies suggest a role of this region in sequential processing of complex stimuli, such as vocalizations (Moser et al. 2009), which bears relation to storage mechanisms (Buchsbaum and D'Esposito 2008; see below). Another possibility is that this area contributes to executive processes or feedback mechanisms supporting the maintenance of activity in sensory regions during transient storage.

On the basis of imaging evidence for the phonological loop, we originally speculated that the language-related circuitry involved a direct connection between auditory areas and Broca's region via the arcuate fasciculus and an indirect projection from posterior auditory regions to the inferior parietal lobe (area 40) and from there to Broca's area (Aboitiz and García 1997, fig. 4 therein). In the same article, we also made mention of a "ventral" pathway from the anterior temporal lobe to anterior Broca's area, involving auditory and visual projections. More recent tractography studies analyzing fiber

connections in the living human brain strongly confirmed this proposal, identifying both a dorsal and a ventral projection from auditory areas to Broca's area. More precisely, in the dorsal pathway, Catani and ffytche (2005) and Frey et al. (2008) described the same tripartite organization previously depicted by us (Aboitiz and García 1997) and consisting of (i) a long, direct pathway connecting the posterior superior temporal gyrus with area 44 (but also area 45), corresponding to the classical arcuate fasciculus, and (ii) an indirect projection consisting of two main pathways: a posterior segment connecting the superior temporal lobe with the inferior parietal region (including the supramarginal gyrus and the angular gyrus, areas 40 and 39), which has been found to fit the medial longitudinal fasciculus (Frey et al. 2008), and an anterior projection from the latter to Broca's region (areas 44 and 45), corresponding to the inferior portion of the superior longitudinal fasciculus (fig. 1). Interestingly, the dorsal pathway was found to be more robust on the left side (Anwander et al. 2007; Catani and ffytche 2005; Frey et al. 2008; Friederici 2009; Friederici et al. 2006; Parker et al. 2005). In parallel to this tripartite dorsal projection, a ventral pathway connecting anterior temporal auditory and visual areas with anterior Broca's region (areas 47 and 45) was evidenced, running mainly via the extreme capsule but also via the uncinate fasciculus (Anwander et al. 2007; Frey et al. 2008; Friederici 2009; Friederici et al. 2006).

The dorsal stream has been related to the processing of the temporal dynamics of complex sounds, mapping acoustic speech signals into frontal lobe articulatory networks (Belin and Zatorre 2000; Hickok and Poeppel 2007; Moser et al. 2009; Zatorre and Belin 2001). These features make the dorsal stream more suitable for including a phonological loop involved in transiently storing and rehearsing sequences of phonological utterances (Moser et al. 2009). On the other hand, the ventral pathway participates in identifying or recognizing auditory stimuli, including speech, and has been related to lexical processes mapping sound with meaning (Buchsbaum et al. 2005; Hickok and Poeppel 2007; Saur et al. 2008). Furthermore, Hickok and Poeppel (2007) claim this to be a bilateral system, being represented in both the left and right hemispheres. In this line, it has been proposed that area 44 of Broca's region, receiving its main input from the dorsal pathway, is mostly involved in phonological and articulatory control, while area 45, which receives an important input from both the ventral and dorsal pathways and projects into area 44, participates in lexical processes related to verbal retrieval (Frey et al. 2008; see also Aboitiz and García 2009). Of note, Friederici et al. (2006) and Anwander et al. (2007) associated the dorsal pathway with hierarchical-syntactical processing. Moreover, they also identified a "middle pathway" connecting area 45A—the deep frontal operculum—with the anterior temporal lobe by means of a connectivity similar to that of areas 47/12, which they claim supports processing of primitive syntactical structures (see below).

## Nonhuman Primate Studies

In parallel with Baddeley's early developments, neurophysiologists identified in monkeys long-range cortical circuits participating in delayed-match-to-sample tasks where either the position or the color of a stimulus has to be maintained in short-term memory for some time before executing a response (Fuster and Alexander 1971). Fuster (1995, 2003) defined this kind of memory as "active memory," implying a broad associative network being activated as a perceptual memory fragment in order to execute an action in the near future. This concept is strongly appealing, not the least because it implies that this kind of memory is a property of the neuronal networks that maintain an activated state for a period of time. Fuster further proposes that rather than being anatomically localized, short-term memory represents a property of sensorimotor circuits and these networks are changeable and overlapping with other sensorimotor networks. Thus, instead of there being a specific "system for memory" in the brain, there is the "memory of systems" in the distinct but overlapping sensorimotor networks. This interpretation is of high interest to us (see above; Buchsbaum and D'Esposito 2008; Jacquemot and Scott 2006), although it may be important to our purposes to keep in mind Baddeley's emphasis on the role of rehearsal (overt or covert) as a mechanism to maintain the activation of these specific networks. Taking this argument into consideration, we will refer to the dorsal pathway of figure 1 as the phonological loop while emphasizing that, strictly, this consists of a reciprocal auditory-vocal sensorimotor circuit that has the property of transiently maintaining activated phonological representations rather than being a dedicated circuit for phonological memory.

In a similar line, a series of articles published by the group of Patricia Goldman-Rakic (reviewed in Goldman-Rakic 1996, 2000) contributed enormously to delimiting specific sensorimotor circuits involved in visual-spatial and object-related short-term memories. These involved occipital-parietal-dorsolateral-prefrontal (dorsal aspect) networks for spatial memory and occipital-inferior-temporal-dorsolateral-prefrontal (lateral aspect) networks for object memory. Goldman-Rakic claimed that the findings did not support the existence of an anatomically separate central executive system but rather that there were separate, roughly parallel networks involved in different modalities of sensorimotor integration that related to working memory in different domains. Perhaps one point that should be stressed in this context is that executive functions must be, by essence, multimodal and integrative and that a unimodal or oligomodal network may not suffice for this function (see Barnard 2010). In this context, perhaps the interaction between areas 9 and 46, in relation to spatial attention, and between areas 9 and 10, in relation to object attention and emotion, should be more thoroughly investigated (Petrides and Pandya 2006, 2007).

The above-mentioned networks were largely associated

with visual processing, however, and there was apparently no direct connection with auditory processes or the phonological loop. Other studies in the organization of the auditory cortex and its projections revealed the existence of two main projection streams in parallel with those observed in the visual system: a ventral one, running through the anterior superior temporal gyrus, conveying information about the intrinsic features of auditory stimuli (the “what” pathway), and a dorsal one, projecting to dorsal prefrontal regions and involved with spatial and dynamic processing (the “where,” or action/movement, pathway; see fig. 2). A recent study indicates that conspecific calls preferentially activate regions associated with the ventral pathway in monkeys (Petkov et al. 2008). These two pathways project to different regions of the prefrontal cortex: the “where,” or action/movement, pathway ends mainly in dorsolateral prefrontal areas 8 and 46 and relates to eye movement control (although there are also projections into Broca’s area; Petrides and Pandya 1988, 2009), and the “what” pathway ends in more ventrolateral areas 12/47 and the border of area 45, the latter related to Broca’s area in humans (see Romanski 2007; Romanski, Bates, and Goldman-Rakic 1999; Romanski et al. 1999).

Interestingly, an auditory domain was identified in macaque ventrolateral frontal areas 12 and 45, in which most neurons preferred vocalizations to other acoustic stimuli, while some neurons were also responsive to visual stimuli (Romanski and Goldman-Rakic 2002). This domain receives projections from a call-selective region of the auditory cortex (see also Gil-da-Costa et al. 2006). More recently, Romanski (2007) reviewed the projections of auditory and visual stimuli in the ventrolateral prefrontal cortex and concluded that a region in area 12/47, bordering area 45, received converging stimulation from both auditory and visual stimuli, especially conspecific vocalizations and orofacial gestures, respectively. Similarly, recent imaging studies in humans indicate that Broca’s area (areas 44/45) and adjacent area 47 are recruited not only for language internal processing but also for the integration of gestural action and speech (Willems, Ozyürek, and Hagoort 2007). Likewise, the homologue to Broca’s area becomes activated with both vocal and manual communicative gestures in the chimpanzee (Tagliabata et al. 2008).

### The Parietal-Inferior-Prefrontal Pathway in the Monkey: Auditory-Visual Processing

In addition to the temporal projections to Broca’s area homologue, strong projections were originally described in the monkey between inferior parietal areas and frontal areas (corresponding to human areas 44 and 45) of the macaque (Petrides and Pandya 1984) and were subsequently confirmed by using more sophisticated tracing techniques (Petrides and Pandya 2009). As in the human, these projections involve the inferior longitudinal fasciculus and have been found to receive

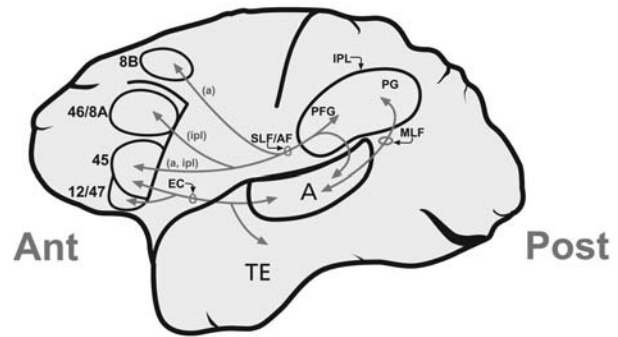


Figure 2. In the monkey, there are projections similar to those of the human, connecting areas homologous to Broca’s (ventrolateral prefrontal cortex; areas 44 [not shown], 45, and 12/47) and Wernicke’s (*A*; posterior auditory) regions. Compared with that of the human, the dorsal stream is poorly developed, and the superior longitudinal fasciculus (*SLF*) and the arcuate fasciculus (*AF*) are difficult to differentiate. As in the human, there are auditory projections to prefrontal areas 8B (mainly auditory [*a*]) and 46/8A (mainly of inferior parietal origin [*ipl*]); these projections are not shown in fig. 1). The ventral auditory projections via the extreme capsule (*EC*) to the ventrolateral prefrontal cortex (especially areas 12/47 and 45) are relatively more developed than the dorsal stream and may represent the main connection system between these regions. *A*, auditory region; *IPL*, inferior parietal lobe; *MLF*, middle longitudinal fasciculus; *PFG*, area PFG of the inferior parietal lobe (proposed homologous to human posterior area 40); *PG*, area PG of the inferior parietal lobe (proposed homologous to human area 39); *TE*, visual area TE, responsive to faces. (Petrides and Pandya 2009; Romanski 2007.)

auditory information from the superior temporal gyrus via the middle longitudinal fasciculus (recall the above-mentioned tripartite organization of the dorsal pathway). Thus, the same overall organization of temporo-parietal projections dorsally and anterior temporal projections ventrally to the inferior frontal region (Broca’s area) has been recently confirmed in both the monkey and the human, a point we made more than a decade ago (Aboitiz and García 1997).

The parietal projections to the inferior frontal lobe have also been associated with hand manipulation and with the “mirror system” for grasping that permits identification and imitation of grasping actions (Iacoboni and Dapretto 2006; Nelissen et al. 2005; see fig. 2). Interestingly, the mirror neuron system includes a component related to orofacial gesture identification, especially vocalization-related mouth movements (Ferrari et al. 2003). The development of a strong mirror neuron system involved in the identification of gestures and, especially, orofacial expressions associated with vocalizations was probably an important prerequisite for the evolution of language and the differentiation of the language-related regions (Arbib 2005; see also Aboitiz and García 1997, 2009; Aboitiz et al. 2006*b*). Furthermore, parietal projections to inferior frontal regions, which control hand manipulation, were likely involved in tool making and possibly coevolved

with phonological networks in early humans in an interdependent interaction in which vocal communication benefited from developments in tool making and vice versa (Ambrose 2010; see also Aboitiz and García 2009).

## An Evolutionary Innovation

In previous articles we have suggested that the increasing development of the dorsal pathway in the left hemisphere was a key element in human language evolution (Aboitiz and García 1997, 2009; Aboitiz et al. 2006a, 2006b), allowing the development of humanlike phonological articulation that in turn permitted the development of a complex vocal communication system based on learning increasingly sophisticated utterances. However, the ventral pathway might represent an ancestral auditory-vocal pathway that is predominant in nonhuman primates. In other words, although the dorsal and ventral cortical networks involved in language can be traced to nonhuman primates, there would be differences in the relative development of these networks, with nonhuman primates emphasizing the ventral pathway and humans emphasizing the dorsal pathway. This is not to say that the ventral pathway has a minor role in modern linguistic processing; as several studies indicate, this pathway is involved in high-order lexico-semantic processing (Saur et al. 2008). Rather, our point is that without a sufficiently robust dorsal pathway controlling complex articulatory processes and bearing a high short-term memory capacity, vocal communication would have never developed as it has in our species. In this sense, although there are many additional networks that contribute (perhaps to higher linguistic functions than phonology), the development of a strong sensorimotor network involved in vocal articulation, allowing the capacity to learn increasingly complex utterances, was a key event that propelled vocal-language evolution. Recently, Rilling et al. (2008) provided anatomical evidence indicating a progressive development of the dorsal auditory pathway from monkey to chimpanzee to human while at the same time the ventral pathway remained relatively stable across species. This evidence suggests a gradual evolution of the dorsal pathway, the chimpanzee having a condition that may be considered intermediate between that of the monkey and that of the human. Nevertheless, the chimpanzee is not characterized by its vocal-learning capacity. One possibility is that having the network does not necessarily imply that it will be used for vocal language. The dorsal pathway may have evolved in the context of increasing motor control in relation to hand manipulation, for example (Arbib 2005), or it may have been a result of increasing regional or overall brain size (Aboitiz 1996). In either case, it probably became co-opted for vocalization and articulatory processing only in early humans. The acquisition of a powerful phonological system permitted the elaboration of increasingly longer utterances and the capacity to put them in long-term memory. This capacity favored the establishment of close social bonds among individuals, thus facilitating

group identity, and there may even have been “personal codes” that permitted the establishment of intimate links between individuals within a single group. Different utterances were used in different contexts, and eventually symbolic meaning appeared by virtue of highly developed cross-modal associations, partly relying on the ventral auditory pathway (Saur et al. 2008). With more complex meanings, some sort of order was needed to disambiguate the different sentences, and the first elements of syntactic order were generated (see Aboitiz et al. 2006a, 2006b).

We cannot establish with clarity when and in which species this loop became functional, but we propose that this process was closely associated with brain expansion (particularly in temporo-parietal regions; see Bruner 2010, in this issue), acquiring its maximal development in *Homo sapiens sapiens*. On the basis of endocast morphology, it is possible that a rudimentary phonological loop was already at work in *Homo erectus*. It is difficult to determine whether Neanderthals had a fully developed loop. Early proposals indicated that their phonatory apparatus was unable to generate the same sounds as modern humans (Lieberman 2002), but these have been seriously challenged by more recent evidence (Granat et al. 2007).

## Short-Term Memory and Syntax

In the above scenario there is still an important gap between the elaboration of a phonological loop and the acquisition of a syntactically ordered language. In this section, we will attempt to provide a link between short-term memory mechanisms and the acquisition and processing of syntactic structure. This is not to state that short-term memory circuits such as the phonological loop explain the complexities of syntax but rather that recent-memory systems (which include phonological and other kinds of short-term memory) participate in the acquisition (and sometimes in the processing) of certain grammatical forms. Thus, those circuits involved in complex language functions strongly benefited from elaboration of short-term memory capacities that helped to maintain these forms online while they were being processed.

Contrary to the structuralist conception that working memory merely imposes limits to syntactical (and linguistic) operation, several recent authors have proposed that phonological memory is an important element in processing and acquisition of syntax and phonology (Gibson 1998; Just and Carpenter 1992; King and Just 1991; Lewis, Vasishth, and Van Dyke 2006; Müller and Basho 2004). Jacquemot and Scott (2006) make a specific case for phonological short-term memory in phonological processing during sentence production and comprehension. Without powerful short-term memory mechanisms, it would be impossible to maintain distinct linguistic elements online while a larger structure is being processed. According to some of the above authors, sentence processing depends on integration, or binding mechanisms linking distant head-dependent relations in a phrase, and on



short-term mechanisms that allow storage of the elements online while they are being processed. Unfortunately, to date the role of verbal working memory in syntax acquisition has been less examined than in vocabulary acquisition. Some have proposed that the ability to store sequences of words plays an important role in syntactic development (see Baddeley 2007; Müller and Bashi 2004), and there is evidence indicating that performance in phonological memory tests predicts mean length of spoken utterances (Adams and Gathercole 1995, 1996). Further studies in this area are strongly needed.

There is more evidence for a role of memory mechanisms in syntactical processing. However, there are disagreements regarding the specific participation of memory systems in this process (see Beaman 2010; Reuland 2010, in this issue). It is likely that Baddeley's restricted concept of phonological working memory may not be sufficient to account for the memory requirements of complex language processing because it is likely that other forms of short-term memory also participate in this process. For example, syntactical processing in the adult is probably automatic to a large extent (Endress and Hauser 2009) and partly depends on corticostriatal networks that have become stabilized as procedural memories that need to interact with episodic memory networks conveying meaning (Ullman 2004). Short-term-memory mechanisms that bridge these elements can be seen as critical to the elaboration of complex language (Reuland 2010).

Some authors claim that there are several separate memory systems subserving the different levels of language processing (phonological, lexical, semantic, and syntactic; Caplan and Waters 1999; Ullman 2004), while others consider these systems as intrinsically associated between them (Lieberman 2002). According to D'Esposito (2007), verbal working memory involves sustained activation of all relevant preexisting cortical language representations (phonological, lexical, or semantic), thus keeping representations accessible via persistent neural activity over several seconds, with the objective to interpret the sentence being processed. In accordance with Fuster's (1995) concept of associative cortical memory, we claim that these different linguistic levels may relate to partly separate but highly overlapping networks that become active during sentence processing, thus contributing to process it as an integrated unit (Aboitiz et al. 2006a, 2006b; see also Hagoort and van Berkum 2007). In this line, an initial sequentiality from higher levels (lexical) to lower levels (articulatory) has been demonstrated in Broca's area during the first 450 milliseconds of a language-production task (Sahin et al. 2009), but this does not exclude the possibility of feedback operations in later stages (Hagoort and Levelt 2009) or persistent activation of the respective networks during ongoing behavior.

There is now a current trend in imaging studies to identify circuits that are specific for syntactical processing and that are not dependent on working-memory circuits (Fiebach et al. 2005). Friederici (2002) has proposed that while syntactic working memory involves the superior anterior portion of

left area 44, syntactic processing relates to the inferior portion of left area 44. More recently, Friederici et al. (2006) and Anwander et al. (2007) observed that the dorsal pathway connecting area 44 and posterior language areas via the inferior parietal lobe might participate in processing hierarchically organized grammatical structures, while their "middle pathway," with a connectivity similar to that of the ventral pathway, but ending in area 45A, subserves processing of simple grammars based on local structures and transitional probabilities (see above). Similarly, Sakai, Homae, and Hashimoto (2003) claim to have identified regions specific for language processing as opposed to those regions that are involved in general mechanisms of verbal working memory. While it is quite likely that the anatomy of neural circuits involved in integrative syntactical processes is not identical to that of the circuits participating in more basic verbal working memory, it is probably also correct to state that there is an important degree of overlap in these networks, an overlap that is minimized by the subtracting methodology used in most imaging studies (D'Esposito 2007; see also Amici et al. 2007). Thus, it is possible that networks involved in syntactic integration or more complex syntactical processes represent an extension of the more basic networks involved in phonological working memory, which may represent a more primitive condition from which more elaborate networks emerged and differentiated. Finally, the fact that there are different circuits involved in syntactical processing than in general working-memory processes does not exclude the operation of short-term memory mechanisms in these additional circuits. Again according to Fuster (1995), short-term memory is a property of cortical circuits, not an anatomical location.

## From Phonology to Syntax

Thus, for the development and acquisition of a complex syntax, robust cortical memory capacities that permitted and facilitated language acquisition in infants and youngsters were necessary. How did these capacities emerge? We propose that the neural circuits associated with online syntactical processing represent an extension of more basic circuits involved in phonological memory and processing. This is supported by the observation that verbal memory is activated in several aspects of complex language processing (D'Esposito 2007). Furthermore, if this proposal is correct, a link should exist between phonology and the acquisition of syntactical rules.

Some authors have indeed claimed that phonological cues permit the listener to extract the syntactical rules of each language (see Mehler et al. 2006). According to Peña et al. (2002), to discover grammatical-like regularities, it is necessary to inspect (phonological) memory traces of the stimuli in order to make generalizations that go beyond the surface form of such stimuli. Furthermore, Nespors, Mehler, and Peña (2003) proposed that consonants and vowels play a different role in language acquisition. While consonants relate more to lexical structure, vowels are more linked to grammatical

structures. Interestingly, a recent study indicates that vowels place processing demands on prosodic systems while consonants relate more to lexico-semantic processing (Carreiras and Price 2008). Similarly, there is an important working-memory literature implying that storage of vowels is more stable than that of consonants and that vowels are also more related to order information in the phonological sequence than are consonants (Drewnowski 1980). Thus, order information is carried principally by vowel sounds, with consonants being more or less strongly attached to individual vowels (Baddeley 2007). Therefore, phonological working memory may be fundamental not only to learning complex vocalizations but also to extracting structural regularities while learning a language.

## Recursion

Finally, syntax has been proposed to contain as a central element the property of recursivity, that is, the ability to iterate sentence production onto previous sentences, producing different hierarchical levels and permitting the manipulation, or movement, of these elements in this hierarchy. This property is largely based on long-distance dependencies that bracket phrases embedded into larger phrases. Such movements are proposed to be tracked by a trace that permits restoration of the canonical order of the sentence (see Chomsky 1991). Furthermore, Broca's aphasics seem to have a specific impairment in tracking the traces connecting moved components during perception of syntactically complex sentences (Grodzinsky 2000). We have proposed, along with others, that some kinds of recursion and syntactical movement are made possible by the existence of powerful short-term memory mechanisms that permit transient storage of the elements bracketing long-distance dependencies and tracking of the moved sentences to their canonical positions during speech processing (Aboitiz et al. 2006a, 2006b). Thus, the perceptual deficit observed in Broca's aphasics may partly reflect a deficit in short-term memory. In fact, there is a wealth of evidence linking Broca's area activation and increasing working-memory load during syntactic processing (Fiebach et al. 2005; Friederici 2004; for review see Aboitiz et al. 2006a, 2006b).

Our position is that the elaboration of a recursive syntax was made possible in the context of a highly elaborated short-term memory capacity for acquiring and processing linguistic utterances. Possibly, the circuits involved in these processes are partly derivatives of a powerful circuit subserving a phonological loop that became integrated with additional circuits involved in extracting meaning and other linguistic functions. The acquisition of a mode of communication based on recursion was probably an additional innovation that further expanded the possibilities of communication and social organization, perhaps triggering the advent of civilization in modern humans. For example, the capacity to elaborate recursive structures may have provided a means to speak about inexistent events, as in the subjunctive mode (Coolidge and

Wynn 2007), which facilitated complex planning behavior and the elaboration of sophisticated technologies and social organizations. Similarly, the capacity to process metaphors has been related to the inferior parietal lobe and may well relate to the activation of this circuit that we have termed the phonological loop.

## Discussion

In this article, we have made an argument for a key role of the phonological loop as an innovation that propelled the evolution of language. Basically, our suggestion is that the elaboration of a sensorimotor circuit in the left hemisphere—involving the posterior temporal region, the inferior parietal cortex as a nodal element, and the ventrolateral prefrontal cortex—served as a scaffolding for the elaboration of increasingly complicated networks that permitted the acquisition of complex language. One fundamental function of this circuit was to act as an auditory-vocal rehearsal system for complex vocalizations, which, contrary to the case of other primates, became highly important for individual communication. This system acquired a large capacity to maintain phonological elements online, permitting a new world of social interactions and communication and opening the possibility of the origin of complex language. The elaboration of further networks involved in linguistic or protolinguistic processing were strongly based on this fundamental template made by the neural circuit subserving the phonological loop. The phonological system may have coevolved with preexisting and overlapping networks involved in motor control, with controlling face and body movements during communication (Willems and Hagoort 2007), and particularly with the ventral auditory projection that served to instantiate phonological sequences into meaningful words (Saur et al. 2008).

Morphological innovations that trigger further evolutionary change are termed key innovations. These consist of specific acquisitions that provide a new evolutionary perspective, opening the possibility for change and morphological diversification. One widely acknowledged example of such key innovations is the feeding apparatus of cichlid fishes, where pharyngeal jaw modifications that enhanced the ability to break down prey freed the jaws from serving their ancestral dual role as a site of both prey capture and prey processing to become devoted solely to prey capture. This feature permitted colonization of an astonishing diversity of feeding niches, resulting in an impressive adaptive radiation (Hulsey, García de León, and Rodiles-Hernández 2006). In our view, the acquisition of a phonological loop played a similar role in human evolution, serving as a key element that made possible an evolutionary pathway that otherwise could have been practically impossible to develop. The phonological loop did not result in such a diversification of species as in cichlids, possibly because of more stringent ecological conditions in the evolution of early humans.

Although this loop is clearly species specific (notwithstand-

ing the existence of precursor elements in nonhuman species, as in any morphological innovation), it is not clear what its genetic basis is. In our view, there was a conjunction of factors, including an increasing brain size, that made possible the elaboration of new circuits (Aboitiz 1988, 1996) and the existence of a selective benefit for those individuals with better phonological capacities. The latter may have encouraged the selection of genes that contributed to the strengthening of such sensorimotor circuits, especially in the left hemisphere. In this context, it is possible that there are genetically determined factors that facilitate the development of specific verbal circuits with high working-memory capacity or even species-specific feature detection systems that permit learning of linguistic regularities (Mehler et al. 2006).

Another issue relates to the role of memory mechanisms in processing or in the acquisition of language. In agreement with Baddeley (1993), we suggest that the primary role of this circuit was the acquisition of novel and increasingly complex phonological sequences. With the elaboration of syntactic rules, including recursion, short-term memory capacity also became necessary to process complex linguistic utterances. Complex syntax implied the development of long-distance dependencies that needed to be kept online or be accessible for rapid retrieval while longer utterances were being processed. Moreover, syntactic movement—that is, the ability to manipulate the canonical order of sentences imposed by basic grammar—is a process in our view strongly dependent on short-term memory capacity. However, short-term memory constraints and phonological constraints as well may have helped to select evolutionarily for the development of syntax and grammar in order to bypass the neurological limitations of these same constraints (see Aboitiz et al. 2006b).

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# Uses and Abuses of the Enhanced-Working-Memory Hypothesis in Explaining Modern Thinking

by Manuel Martín-Loeches

Evidence is reviewed here that is contrary to the idea that a small enhancement in working-memory capacity determined the emergence of the modern human mind as something radically different from previous human minds and materialized only in figurative art, particularly therianthropes. When reviewing the neurological and psychological literature on working memory, it is clear not only that working-memory capacity varies extensively within modern populations but also that working memory and general intelligence are becoming highly synonymous. In this conception, working memory could appear less obscure, and the idea of a gradual increase in working-memory capacity along the human lineage would appear to be a parsimonious scenario. In a different vein, the neurological underpinnings of art are reviewed. The geometrical engravings from Blombos Cave, as old as 100,000 years, appear to probe the presence of art in its plainest sense in Africa by that time, much earlier than the emergence of therianthropes in Europe during the Upper Paleolithic explosion of art. Noticeably, the Blombos Cave engravings have much in common with present-day art. The possibility that most therianthropes are the result of an unsuccessful attempt to merely draw animals is also discussed.

An enhancement of the working-memory capacity (enhanced working memory [EWM]) appears to be a parsimonious and sound proposal for explaining modern thinking. However, as it was originally outlined, this hypothesis conveyed (even if only implicitly) the radical idea that it was intended to be *the* solution to the humankind enigma. In this regard, Coolidge and Wynn's (2005, 2006) line of reasoning appears to suggest that EWM implied a sudden and totally new change in human cognition, accounting for the advent of an unprecedented mind on Earth. This "revolution" would have occurred in Europe about 30–40 kya, and as a result, art and religious thought would have emerged, giving place to a cultural explosion during the Upper Paleolithic (Coolidge and Wynn 2005, 2006).

In my view, however, Coolidge and Wynn may have overlooked several lines of evidence against a truly abrupt and qualitative transformation of the human mind. It will be the main purpose of this article to comment on this evidence in light of the EWM hypothesis. Accordingly, I will review some data indicating that the improvement occurring in the human

mind that gave rise to modern thinking might have been a minor one adding to already attained previous advancements within the genus *Homo*. As an outcome, the achievement of the modern mind would have been a gradual phenomenon rather than a sudden one, the border between the modern and the nonmodern mind being highly indefinable. Furthermore, I will review evidence revealing that the emergence of the modern mind (admittedly, a mind that has been categorized in such a way) could have arisen long before the Upper Paleolithic explosion 30–40 kya in Europe. Instead, a better time and place would be some 100 kya in Africa. Moreover, it also appears probable that the modern mind did not come to a dead end after emerging in Africa by that time but underwent further enhancements throughout subsequent years, including current times.

## Conceptions of Working Memory

There are various ideas about what working memory is. By collecting several proposals, we could arrive at a comprehensible, simple, and schematic conception of working memory as follows. First of all, from the neurological point of view, working memory is understood as the sustained neuronal firing selective to a stimulus feature no longer present in the environment but needed to be kept over short periods of time

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**Manuel Martín-Loeches** is Professor of Psychobiology at the Center for Human Evolution and Behavior, Universidad Complutense de Madrid–Instituto de Salud Carlos III, Monforte de Lemos, 5, Pabellón 14, 28029 Madrid, Spain [mmartinloeches@edu.ucm.es].

for immediate access and evaluation (Compte 2006). This has also been known as persistent activity, which has been reported for many brain cortical areas (Fuster 1995; Goldman-Rakic 1995) and which appears to be involved in tasks other than working-memory tasks, such as oculomotor coordination and head-direction movements (Major and Tank 2004). It appears, therefore, to be a general computational strategy developed by the nervous system.

This depiction is based mostly on animal research. When working memory has been applied to human cognition, however, it has usually gone beyond the persistence of activity representing perceptual features by also engaging the persistent activation of knowledge stored in long-term knowledge. The latter would comprise specific knowledge (facts stored in both episodic and semantic memory) as much as computations needed to process information and the outputs of these computations (MacDonald and Christiansen 2002). Overall, the main idea is that working memory implies the persistent (though always transient) activation of neural circuits representing stimulus features, long-term knowledge (including computational rules or algorithms), and the results of the computations performed so far.

Keeping this conception of working memory in mind (more properly, in our working memory), it might be easy to understand that EWM appears synonymous with enhancing the number of persistently activated neurons on behalf of a particular task, that is, an increase in the number of neurons that can be activated simultaneously (Aboitiz et al. 2006; Martín-Loeches 2006). Accordingly, the genetic mutation that gave rise to the final achievement of EWM could have occurred via one of the following possible causes for this phenomenon or a combination of them (indeed, they are not mutually exclusive): (a) an increase in the number of neurons available and/or of the complexity of the neural circuits involved (Coolidge and Wynn 2005); (b) the possibility of using additional metabolic resources for keeping active a larger number of neurons (alternatively, the possibility of decreasing the metabolic costs of keeping neurons activated so that more neurons can be activated with the same total costs; many possibilities could be raised here, such as increases in the synaptic efficiency both at pre- or postsynaptic levels [e.g., Balter 2007]); (c) a prolongation of the (decay) period of neuronal firing following activation boosts, a relevant feature of working memory for computational purposes (Lewis, Vashith, and Van Dyke 2006).

Because working-memory capacity appears to be a highly heritable trait, this has been taken as support for the proposal by Coolidge and Wynn (2005) that a single additive mutation could have been responsible for EWM. However, the number of genes contributing directly or indirectly to working-memory capacity may be large. Indeed, many of the genetic differences between our closest relatives, the chimpanzees, and our species appear to be related to genes involved in processes with direct or indirect consequences for working memory. For example, two genes involved in neural cell proliferation

(ASPM and MCPH1) and related to the number of existing neurons have undergone an accelerated evolution in the human lineage and, what is more, continue to evolve adaptively in humans (Evans et al. 2005; Mekel-Bobrov et al. 2005). This is also the case for the gene NRCAM, which participates in the regulation of neuronal connections. Several other genetic regions relevant to this feature are called “human accelerated regions” and relate to interneuronal connections, namely, by expressing cadherines (proteins involved in cell adhesion, i.e., synaptic contact; Prabhakar et al. 2006). Additionally, certain genes, such as SIGLEC11, involved in glial expression (affecting neural metabolism and synaptic processes) have been found to be human specific (Hayakawa et al. 2005).

Another good candidate for contributing to working-memory enhancement has been, traditionally, the FOXP2 gene. Anomalies of this gene may cause both structural (number of existing neurons) and functional (number of activated neurons) abnormalities in certain brain regions related to language (Vargha-Khadem et al. 1998). However, the recent finding that this gene was shared with Neanderthals (Krause et al. 2007) certainly rules out the possibility that this gene was responsible for the final achievement of modern thinking.

As can be seen, there are a number of genetic candidates for the development of EWM. Accordingly, considering genetic evidence and in the light of the working-memory definition from the neuronal point of view outlined previously, the idea of an abrupt change in the human mind appears to be somewhat misleading. Instead, it would be more plausible to consider the idea of multiple and successive enhancements in working memory along the human lineage. Furthermore, because some of those relevant genes appear to be still evolving, there is the possibility that our mind has further evolved since it became modern and that it is still evolving. Consequently, I suggest that there have been successive, gradual, and probably subtle enhancements of working memory, with multiple factors contributing to this end, since human and chimpanzee lineages ultimately diverged.

Indeed, if we agree that modern *Homo sapiens* is the most intelligent creature on Earth (which is actually commonplace, tautologically included within the name *H. sapiens*), we have to accept that modern *H. sapiens* is the creature with the largest working memory on Earth. Both intelligence and working memory are becoming relatively synonymous in contemporary psychology. Recent proposals stress this intimate relationship, if not entire overlap, between working memory and intelligence (Colom et al. 2004; Unsworth and Engle 2007). Accordingly, if we agree that modern human intellectual ability has been the consequence of a gradual process of evolution, we must also agree that EWM has been attained gradually. It appears plausible, therefore, that EWM was achieved following multiple genetic mutations, none of them more outstanding than the others, and the border between modern and nonmodern minds becomes rather blurred.

How could EWM explain the modern mind? Let us examine the case of language as a representative example. With

*“The good journalist who the corrupt senator attacked was prized”*

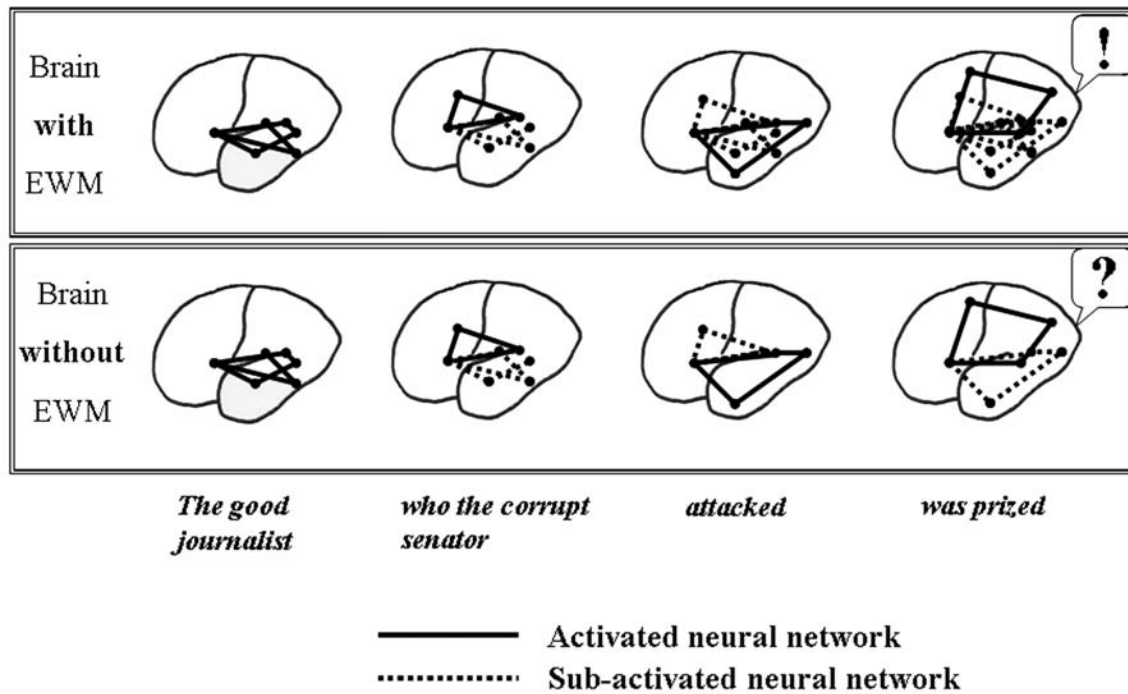


Figure 1. The neural network with enhanced working memory can successfully decode the sentence, but the network without enhanced working memory cannot.

an enhancement in working-memory capacity, human language can be significantly improved, achieving the unique features that characterize modern human language. In this regard, a main central process in human language is the comprehension of sentences. A sentence is composed of several words, and it is the human brain’s goal to determine what the relationships between these words are, relationships based on a structure with some degree of hierarchy.

In the sentence “The little cat is beside the big dog,” the adjective “little” refers to “cat,” and the adjective “big” refers to “dog,” whereas both animals have some type of mutual relationship (one is beside the other). This is true even though, and according to the syntactic structure of the sentence, we are primarily speaking about one of the animals (“the little cat,” which is the subject of the sentence). Interestingly, this sentence could probably have been understood by a brain with a working-memory capacity less than that achieved by modern humans, for example, a Neanderthal mind, and even possibly others. But now consider the following sentence: “The good journalist whom the corrupt senator attacked was prized.” There is a relatively long distance between “was prized” and “the good journalist,” together with some disturbing elements in between: another participant (“the corrupt senator”) and another verb (“attacked”), regardless of which we have no trouble in recognizing “the good journalist”

as the subject of the main sentence and “was prized” as the main verb in the sentence, attaching this verb to that subject. A Neanderthal probably could not understand this sentence, given that it is both long and contains relationships between the words that are nonlinear. To understand a sentence as the latter (as well as notably longer and more complex examples that could have been brought up here), we need the working-memory capacity of modern humans. With EWM, we can (easily) keep activated or subactivated several elements in working memory until they are attached or related to their corresponding counterparts even if there is distance between them and confusing elements appear in between (fig. 1).

By having a complex language able to define complex relationships of the real world, we have a tremendously powerful tool to better comprehend the complexities of the real world. In other words, we would have an improved way of reasoning. However, this does not necessarily mean that it is language that improves thought (e.g., Pinker 2007). Instead, an increase in working-memory capacity could be a general-purpose neural mechanism explaining both a better reasoning capacity and complex modern language.

Before going on, I think it is crucial to outline a last reflection on working-memory capacity if we want to better define what EWM might actually mean. It is important to perform systematic studies comparing our working-memory



capacities with those of our closest relatives, the chimpanzees (though other species could also be good enough). This is work to be done. Indeed, we have several parameters to focus on. For example, does our EWM imply that we can keep in our working-memory store a higher number of items than monkeys can? Or can our EWM keep a similar number of items but the quality and/or complexity of each item can be larger in our species? The answer may indeed depend on the type of knowledge to be retained. A recent discovery by Inoue and Matsuzawa (2007) shows that chimpanzees can be even better than us in remembering visuospatial sequences of numbers. Whatever the answers to these questions, how long is the decay time of stored items in each species? Could it be (as well) that our items are kept longer? Does the duration parameter also depend on the type of information to be stored and manipulated? Specific answers to these questions will assist us with defining in depth what EWM means for modern thinking.

### Markers of Modern Thinking: The Special Case of Art

Regardless of whether the modern mind was achieved gradually or suddenly, it cannot be denied that it appears as qualitatively different from previous human minds. There are some features of modern human thinking that appear distinctive. Several of them have been shown to appear in Africa over 200 kya. These include the manufacture of points, grindstones, and blades as well as pigment processing (McBrearty and Brooks 2000). Some others, such as the use of bone tools, mining, or fishing, are more recent achievements but again far from the 30–40 kya proposed for EWM (actually, closer to 90 kya). This evidence supports a gradual achievement of modern thinking.

Perhaps one of the most outstanding and recently achieved features of our mind is the production of art. In the following, I will focus on this feature in depth because it constitutes evidence that EWM could have been a matter of gradual achievement and that it might have arisen long before 30–40 kya out of Europe.

Contrary to the classical hypothesis that a human revolution occurred in Europe by 30–40 kya, yielding both art and religion as a main outcome (together with other distinctive achievements), art and religion might be two different and distinguishable phenomena that might have arrived independently. Yet art appears to leave a more clear signature in the archeological record. Is this the final evidence for modern thinking? The answer may depend on our conception of art.

Coolidge and Wynn (2005) suggest that even if earlier samples of art have been found, the modern human mind did not arrive until therianthropes appeared in Paleolithic art about 30 to 40 kya in Europe. These drawings, which mix human and animal features, would be evidence, according to these authors, that a modern mind able to combine different

entities had been achieved. This disregards other types of art, such as geometrical patterns or depictive images, as probing the presence of modern thinking. Accordingly, geometrical patterns and depictive images would be a product of a pre-modern mind. However, the evidence to support this assertion is not as strong as it appears. The geometrical patterns of Blombos Cave, as old as 100 kya, could probe the presence of art in its plainest sense. To support this argument, we need first to take a look at what cognitive neuroscience tells us about art.

Ramachandran and Hirstein (1999) outline a basic idea: art produces pleasure. For every piece of art, the artist, consciously or not, would make use of some procedures that better and pleasantly excite the perceptual areas of our brain. Visual art would be a good tool, accordingly, to overexcite visual brain areas. Hence, to be considered artistic, a piece of art must overexcite perceptual areas more than natural stimuli, and by this means, it should evoke pleasure to the perceiver. The proposal by Ramachandran and Hirstein has been recently endorsed by a number of authors (e.g., Smith 2005)

This overstimulation of perceptive areas would produce pleasure as a consequence of the direct neural connections between those regions and the limbic system, the brain system for emotions. One basis for this state of affairs is the fact that our cognitive system is well suited to feel satisfaction, or emotional responses, whenever something relevant in the environment is discovered. To discover a prey, or a predator, hidden in vegetation (or far away and therefore hard to see) would represent a success to our perceptive system, and, consequently, it would trigger an emotional response. It is a basic survival mechanism. For this reason, both our system for reasoning and decision making and our emotional system are closely related. Art might take advantage of this mechanism.

Ramachandran and Hirstein (1999) propose eight principles by virtue of which art exploits this mechanism of overexcitation of our perceptual system that produces pleasure. It is worth making a brief comment on these principles here. Overall, it has to be remarked that all of them are purely perceptual principles.

The first principle is exaggeration: exaggerated attributes are more strongly appealing than normal ones. “Supernormal” stimuli, as caricatures or nude bodies with larger-than-real sexual attributes, as is the case of prehistoric Venuses, would powerfully summon our attention. The second principle states that if one of the features of the stimulus (as shape or color) is emphasized, the stimulus will be more rewarding because all of our attention can more easily focus on that feature. As an example, many artistic pieces are black and white or, even more often, made just outlining a shape. Indeed, a vast majority of Paleolithic art consists of outlined shapes, and these include the certainly profuse engravings. The third and fourth principles directly relate to our capacity to detect figures against background. In this regard, the third principle states that grouping several elements of the perceptive field (e.g., dots) as constituting parts of a single entity

leads us to discover “hidden” figures and, hence, to attain some degree of pleasure. The fourth principle stresses the relevance of exaggerated contrasts in the stimulus, which facilitate the detection of individual figures.

The fifth principle deserves further comment. It is probably one of the most intriguing, having been highlighted also by other authors (Zeki 1999). According to the fifth principle, resolving perceptual problems is rewarding. That is, whenever our perceptual system has to undertake an effort in order to completely understand a stimulus, pleasure is assured. For this reason, an incomplete nude figure may be more appealing than a totally nude one, because it is our brain that completes what is not visible (but just suggested). Also for this reason, many figures are not detailed, and even many incomplete artistic items can be found. This has in fact been alleged as a reason why Michelangelo did not finish several of his most notable masterpieces: what Michelangelo had in his mind could not be represented in the real world because it may have been more perfect than anything in the real world (Zeki 1999). Beneath this principle is the idea that one of the main purposes of our brain is to seek constancies and essences, to seek relevant points. This is not an artistic ability, indeed, but rather an overall cognitive one, one of the main goals of our cognitive system. However, even if discovering these essences is based on numerous perceptual experiences, its outcome is not perceptual in nature, and, therefore, it is not easy (if at all possible) to retrieve it to the real world in the shape of an actual depiction, engraving, or sculpture.

For instance, a chair is a chair even if it has four, three, or even one (big) leg or whatever the color and material it is made up of. In fact, many variants in shape, or any other visual feature, could be brought up here, but a chair would still be a chair despite these variations. For this reason, it would not be easy (if at all possible) to draw the “essence” of a chair. This same (fifth) principle would also apply when we are able to “discover” figures out of the clouds, much as when Paleolithic artists “saw” figures in the rock walls where a piece was going to be outlined using natural edges and shapes as parts of paintings or engravings. Overall, perception is always a process in which bottom-up and top-down processes interplay constantly. That is, perception is the result of both what is actually before our eyes and our previous knowledge of the world. Art exploits to a high degree top-down processes involved in perception.

Ramachandran and Hirstein (1999) propose three more principles essential to art. According to one of these, generic visual interpretations are preferred to concrete or very specific representations (this principle indeed relates to the previous one). Another principle states that metaphors would be preferred because these mark and stress specific aspects of reality that can hardly be seen at first sight. Symmetry is a matter of the last principle: symmetry is appealing for us, usually as an indicator of health and perfection.

As can be seen, all the principles proposed by Ramachandran and Hirstein (1999) have as a common element the fact

that art is more appealing the greater the extent to which it outweighs reality, the extent that it goes further than the real world. When this happens, our attention is strongly summoned, and we feel pleasure.

After considering these principles, it appears evident that, together with perceptual areas and limbic regions of the brain (devoted to perception and emotion, respectively), art must involve the prefrontal cortical regions. Indeed, one of the main nuclei within the limbic system is the amygdala, which in turn has strong connections to our intellectual system in the prefrontal lobes, including the dorsolateral prefrontal cortex and the anterior cingulate gyrus, the system that permits us to plan, anticipate, and decide (De Martino et al. 2006). Interestingly, these regions have undergone accelerated evolution in the human lineage and/or display a particular neural organization in the primates, particularly in humans (e.g., Schoenemann 2006). These regions play a principal role in the coordination of the work of posterior (perceptual) brain regions and also resolve what is relevant and what is not relevant. Furthermore, they are crucial to extracting the “essences” of the perceived world, a core purpose of art. For these reasons, it is not unexpected to find studies in which the dorsolateral prefrontal cortex plays an outstanding role in beauty perception (Cela-Conde et al. 2004). If art produces pleasure, and if this pleasure is closely linked to brain areas strongly responsible for our highest levels of intelligence and working memory (e.g., Kane and Engle 2002), it is far from surprising that a species with such a degree of intelligence and working memory as ours gave rise to art eventually.

Accordingly, the emergence of art required the expansion of certain regions of the brain: the perceptual and prefrontal cortical areas as much as the cingulate gyrus. These regions have, in turn, a core role in consciousness, in both its perceptual and volitional facets (e.g., Lamme 2006). This agrees with the assertion by Solso (2003) that only a mind with a high degree of consciousness—able to voluntarily manipulate a large amount of information simultaneously (this is a good definition for working memory)—can generate art (Solso 2003). This may be why only humans have art.

However, the expansion of these regions and the achievement of higher levels of consciousness and working memory were certainly not sudden processes. Rather, they were the result of progressive evolution along the human lineage. This might be the reason why samples of possible, even if uncertain, art expressions can be found belonging to periods long before the supposed appearance of the modern human mind, such as the controversial Berekhat Ram figurine, dating more than 300 kya. Perhaps we should not disregard other ancient signs of beauty or “art sense,” for example, the apparently senseless symmetry of the handaxes designed as long ago as those by *Homo ergaster*. Indeed, it is not hard to appreciate their beauty, and they might be accepted as rudimentary pieces of art. What is more, they are exploiting one of the principles established by neuroscientists as belonging to art. Symmetry in handaxes is not a fortuitous “artistic” expres-

sion; it is due neither to chance nor to the result of natural factors. Even if rudimentary and acceptably incomplete as art, we already have some of the art principles present in very early times.

Several other artistic signs are more ambiguous, such as the engravings found in Bilzingsleben, Germany. The four bones displaying a series of parallel lines that could actually be the result of the use of tools to extract meat out of bones. In Zhoukoudian, close to Beijing, 20 pieces of quartz with no apparent use were found to have been collected by *Homo erectus*. However, it is true that some birds also collect bright objects.

Although controversial and debatable, these and other possible art samples may have been in place before the emergence of the modern mind. But it is also true that apart from intentional symmetry, they all are dubious and could be interpreted as the result of fortuitous circumstances, not as deliberate artworks. Part of the scientific community, nevertheless, strongly supports the validity of several of these ancient pieces as true art. I am personally not among them, but I do believe that the existence of debates and doubts about these products shows that the border between the absence and the presence of art may indeed be indefinable. This would in turn support my suggestion that the achievement of our high levels of working memory and consciousness, necessary to yield art, was a progressive accomplishment.

There are ancient pieces of evidence that cannot be the product of chance or natural variables, and these are clearly the product of a modern human mind. Some of them are as old as 100 kya and were produced in South Africa, much earlier than the proposed emergence of the modern mind about 30–40 kya in Europe. The Blombos Cave engravings on ochre stones might conform to a tradition occurring over a period of 25,000 years that consisted of crosshatched designs, dendritic shapes, parallel lines, and right-angled juxtapositions (Henshilwood, d'Errico, and Watts 2009). These engravings appear to be deliberate (i.e., not incidental marks secondary to utilitarian processes), and they indicate precise neuromotor control (Henshilwood, d'Errico, and Watts 2009; Henshilwood and Dubreuil 2009). But interestingly, the Blombos Cave engravings also meet the requirements to be considered art. Noticeably, in this regard the Blombos Cave engravings excite our more primary perceptual areas of the visual system. Cortical regions in Brodmann areas 17 and 18 (occipital regions, the first processing landmark in the cortical visual system) are particularly specialized for seeking linear patterns in the environment and fit well those appearing in the Blombos Cave engravings. In this sense, therefore, the Blombos Cave engravings might be overstimulating our primary visual areas, and their contemplation may evoke in us the same pleasure that it evoked in their creators. This is art, at least according to a neuroscientific perspective. What is more, we have closely similar pieces of art in current times, such as some works by the artist Jesús Rafael Soto and certainly many others. In summary, there is the argument that

the Blombos Cave engravings may suggest an early stage in art production before the emergence of figurative art and therianthropes and, therefore, before the modern mind. Alternatively, there is my present argument that the Blombos Cave engravings meet the neuroscientific requirements of art and, therefore, that figurative art, therianthropes, and these engravings are produced by the same modern minds.

However, to better depict the whole picture, we need to fill the gap between art produced some 100 kya and the Chauvet paintings of some 32 kya if we do not want to disregard the latter as reflecting the true onset of a human mind revolution. We also need to explain why the amount of art noticeably proliferated that much by 30–40 kya in Europe. This, which has been considered as evidence for a mental revolution, could rather be the result of other circumstances. Let me attempt to fill this gap.

Indeed, several partial pieces of evidence seem to indicate that from 75 to 30–40 kya, there is not a complete gap. In Kostenki, Russia, the remains of a human population as old as 45–42 kya have been recently found (Anikovich et al. 2007). These findings comprise what may be considered the oldest known sculpture so far: a bone fragment possibly representing an unfinished human head. I would not go so far as to assert that the figurine was unfinished for the same reasons that compelled Michelangelo to leave unfinished several of his sculptures, but I do believe that this is evidence that the modern mind did not suddenly emerge in Europe only 30–40 kya.

The same modern human population that dispersed from Africa some 80–60 kya (Goebel 2007; Mellars 2006) was probably the one traveling to Australia by 60 kya or even earlier. There are ochre remains in caves of Australia produced by that time and even some geometric patterns that might also be that old (Flood 1997). What is more, much of the subsequent art production in Australia displays striking resemblances to European art occurring after the hypothetical human revolution, including handprints on the walls. We humans of nowadays have lost the knowledge of the reasons for these handprints, but it is interesting that human populations located at opposite ends of the world used handprints in similar time periods: Australia is just at the antipodes of the places in Europe where the art revolution (and, then, the hypothetical last enhancement in working memory) supposedly took place. This rather suggests that a common population using handprints and other commonplaces of Paleolithic art appeared elsewhere and, from there, it expanded to Asia, Europe, and Australia. Other possibilities imply calling for human universal art archetypes, but this is certainly not a solid argument even if it is admissible.

Nonetheless, it is true that dating the oldest Australian art is still a controversial matter, and more research is needed in this regard. Accordingly, it could not totally be discarded that later populations migrated from Europe to Australia, giving place to Australian art, but this is certainly not a parsimonious possibility.

I assume, therefore, that the modern mind was already present in Africa at least some 100 kya and from that place it expanded to other places, including Europe and Australia. However, we should explain the explosion of European Upper Paleolithic art that took place some 30–40 kya. Disregarding the possibility that the human mind suffered a radical change or improvement by such time in Europe, I prefer, as others have, to call it a cultural explosion. That is, there was a revolution in the amount of art, not in the quality of art (and, therefore, not in the quality of the minds of the artists as a consequence of an exceptional genetic mutation); it would have been an overwhelming production of art.

To explain why so much art appeared in Europe by some 30–40 kya, local circumstances can be brought into play. In principle, although a final working-memory enhancement can not be totally rejected, other plausible and more parsimonious explanations fit. One is, of course, the presence of particular taphonomic circumstances by virtue of which the relative abundance of caves in Europe provided not only good canvas for Paleolithic art but also excellent preservation conditions. But several other complementary explanations are possible. For instance, Lewis-Williams (2002) has proposed that the abundance of art in Europe by this time is mainly a consequence of our encounter with Neanderthals. In this sense, a large amount of art production would have been used as a way of demonstrating the intellectual superiority of our species, as an attempt to impress our closest evolutionary relatives. Another possibility, stressed by Guthrie (2006), is that most of the Paleolithic art in Europe was created by teenagers. Indeed, given the quality and the content of most of the art from that period, as well as the size and the shape of the numerous handprints found in the cave walls, Guthrie convincingly argues that the creators of most European Paleolithic art were indeed teenagers. In this view, good-quality art would be an exception, not the rule, and a demographic explosion would be the most plausible reason accounting for that art explosion.

However, we have a pending matter: therianthropes. Guthrie, who is not only a natural historian but also a skilled sculptor, claims that most of the production of theoretical therianthropes is the result of failed attempts to represent animals and not human-animal mixtures. Accordingly, most (if not all) therianthropes are in fact the products of bad and inexpert artists attempting to draw animals and only animals. What appear to be human bodies or legs together with animal heads or other body parts are rather the result of a mistaken observation of the real shape of the body parts of the represented animals. Even several of the most well-known therianthropes, such as the famous “shaman” from Trois Frères in France, could be explained in this way. Although there is substantial criticism of Guthrie’s claims (e.g., White 2006), I find his interpretation of therianthropes plausible and parsimonious.

Consequently, real therianthropes would be the exception and not the rule. Is this exception enough evidence for the

emergence of a different mind with an EWM relative to that of the creators of the Blombos Cave engravings? From my point of view, therianthropes are not a strong argument for a final EWM occurring 30–40 kya in Europe because more plausible and parsimonious explanations are available. This is also the case for the vast increase in the amount of art in Europe occurring at this time. And at the least, neither therianthropes or the increase in art in Europe at that time is a strong argument for a qualitative change in the human mind.

A final comment regarding the comparison of the Blombos Cave engravings with therianthropes deserves some space. Indeed, therianthropes (and figurative art in general) would be stimulating cortical brain areas devoted to higher (i.e., deeper) levels of information processing than those excited by the Blombos Cave engravings. In this sense, the existence of an evolution of the depth of processing involved in art could be claimed, and, in line with this, an evolution of the mind of the artists could be assumed. Although admissible, this should not necessarily be the case, because as we have seen, modern (current) artists also exploit the overexcitation of primary visual areas. Moreover, there are many primitive societies, even several currently extant cultures, living without figurative art expressions, not to say therianthropes. This is the case of the tribal people in Amazonia, as well as of people from many other places throughout the world (Levinson 2006). Rather, geometrical drawings are instead the rule in many societies. Are they premodern humans?

## Last Reflections and Concluding Remarks

Despite all my arguments, I could find admissible the proposal that moving from the Blombos Cave geometrical engravings to figurative art and then to therianthropes suggests different milestones in the evolution of an EWM. But this trail, if real, could better support a gradual evolution of the same (but already modern) mind throughout the millennia. This evolution could be due to both cultural and neurophysiological factors (based on genetic changes that are still occurring) cumulating through time, though each one is of small consequence when considered in isolation. In this line, we should also have to admit that the current human mind is not the same as that of Neolithic times, which in turn would also be different from that of Paleolithic times.

But then, a big problem remains: we should start defining what exactly we mean by a modern mind or modern thinking. With such a definition in hand, we could easily define what a nonmodern mind is. Such a definition might also help us to definitely decide whether the Blombos Cave engravings (and, then, modern art using similar geometrical patterns) are evidence for a fully modern mind. The same would apply to the Russian figurine of Kostenki, to ancient art remains in Australia, or even to figurative art other than therianthropes (provided the latter are real). Overall, it is my impression that it is better to speak of a gradual improvement of working memory and then of intellectual abilities in a process that did

not come to an end either in Africa 100 kya or in Europe 30–40 kya; instead, the process still goes on.

As an additional mechanism to be considered as playing a role in this story of gradual improvement, we could mention a proposal by several authors (e.g., Calvin 2004) according to which our cognitive capabilities would have improved from one generation to the next by the fact that a given generation has been exposed to the advances achieved by the previous one, this exposure occurring during early stages in the ontological development. This, by itself, would yield wider and more complex neural circuits when the referred generation becomes adult, achieving cognitive improvements not accomplished by previous generations. These improvements would in turn be transmitted to the next generation, and the cycle starts again. Although the reach of this sort of mental evolution might be somewhat limited if no genetic changes come into play, it could at least explain why the same mind could yield different products throughout the millennia without calling into play the advent of a totally new mind.

In conclusion, it was not one small enhancement but many small enhancements in working-memory capacity, in both the amount and the quality of the material to be stored and treated in working memory, that gave place to the modern mind. These small enhancements produced a rather gradual working-memory improvement and might have occurred relatively often during the whole period since the human and chimpanzee lineages diverged, disregarding a critical landmark or point after which we “crossed a Rubicon” unraveling humankind before and after that point.

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# Morphological Differences in the Parietal Lobes within the Human Genus

A Neurofunctional Perspective

by **Emiliano Bruner**

There have been very few morphological studies regarding brain parietal volumes. This is probably a result of the fact that their boundaries are rather difficult to establish. Functions of the parietal lobes that have already been documented range from visuospatial integration, category recognition, and praxis to orientation, numerical processing, and speech decoding. It has been hypothesized that the parietal lobes have had a major role in the evolution of the human brain because of their morphological changes. As brain size increases, they undergo relative flattening in nonmodern humans. This pattern is stressed in Neanderthals, which show, however, a certain widening of the parietal volumes. Only *Homo sapiens* shows a generalized enlargement of the entire parietal surface. Comparing the modern endocranial geometry with the configuration from extinct species, it seems that the lower parietal areas are displaced inferiorly. This suggests that the upper areas, or the intraparietal sulcus, have been involved in these morphological variations. The role of the upper parietal lobule in the recognition and codification of the outer spatial environment and the associated integration between the outer frame and the inner perceptions would seem to indicate that such morphological changes may also have been related to important neurofunctional differences.

*We perceive space in terms of the spatial locations and relations between objects and events within that space, and the relation of these to our own bodies, and the relations between our body parts, and our relation to the direction of gravity. (Mountcastle 1995:383)*

For more than a century, human paleontology largely dealt with descriptive approaches to single anatomical features. This was mostly a result of the fragmented nature of the fossil records. A large amount of literature concerning cranial evolution was (and still is) devoted to considering the simple presence/absence of characters or to quantifying the variation of given morphological diameters. However, since the second half of the twentieth century, the skull has been recognized as an integrated structure in which soft and hard tissues interact physically. This produces pressures and tensions through which the genetic program transforms the phenotype during morphogenesis. This kind of approach represents the basic framework of functional craniology (Moss and Young 1960) and offers new perspectives in the interpretation of the

evolutionary processes associated with the evolution of the human genus (Bruner 2007).

The neurocranium generally varies in size (growth) because of brain pressure, and it changes in shape (development) because of tension exerted by connective layers such as the falx cerebri and the tentorium cerebelli (Moss and Young 1960). While the lower parts (cranial base) show rather complex dynamics associated with multifactorial and polyphasic processes (see Bastir, Rosas, and O'Higgins 2004; Bruner and Ripani 2008; Lieberman, Ross, and Ravosa 2000; Neubauer, Gunz, and Hublin 2009), the upper parts (vault) display more linear relationships: the brain "pushes away" the vault bones, and the interaction between the meningeal sheets and the sutural organization "covers" the gap by adding bone tissue and adjusting the curvature (Enlow 1990).

Naturally, there are many variables involved, and the precise process has yet to be fully understood. Some bones come from dermal precursors, while others come from cartilaginous structures. More interestingly, some areas are mesodermal in origin (such as the parietal bones), while others come from the neural crests (such as the frontal bones; Jiang et al. 2002; Morriss-Kay and Wilkie 2005). Finally, the structural strains caused by brain growth, the vascular system, and the connective meningeal layers probably interact physically and biochemically to regulate morphogenetic processes at the sutures

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**Emiliano Bruner** is Research Group Leader in Hominids Paleo-neurology, Centro Nacional de Investigación sobre la Evolución Humana (CENIEH; Paseo Sierra de Atapuerca s/n, 09002 Burgos, Spain [emiliano.bruner@cenieh.es]).

(Henderson, Longaker, and Carter 2004; Warren et al. 2003). Therefore, instead of considering single features, cranial evolution would be better interpreted in terms of integration and covariation patterns where the phenotype is considered to be the result of biological interaction between structural and functional units (modules), in both its ontogeny and its phylogeny (Breuker, Debat, and Klingenberg 2006; Klingenberg 2002).

Paleoneurology refers to the anatomical and morphological studies of the fossil endocasts (Bruner 2003; Falk 1987; Holloway 1978) and their possible implications in cognitive and cultural contexts. Ever since the early studies regarding endocranial variation of extinct hominids, the parietal areas have represented a debated and sensitive issue. Many efforts were made to establish whether the Australopithecines have a lunate sulcus more posterior than that of the living apes. Ralph Holloway hypothesized that in the genus *Australopithecus*, the posterior displacement of the lunate sulcus is related to a relative enlargement of the posterior parietal cortex (see Holloway, Broadfield, and Yuan 2003). Were this to be the case, the change would suggest an early reorganization of the brain in the first hominids around 5 million years ago; morphological changes in the parietal areas before the changes in the frontal lobes; and some cognitive variation associated with visuospatial integration, social communication, and savannah habits (for a review, see Holloway 1995). Furthermore, by analyzing the endocranial morphology through surface stereoplotting, Holloway (1981) underlined a large source of morphological variation in the parietal areas in both the extant and extinct hominids.

More recently, the endocranial morphological variation in the human genus was analyzed by using geometrical models and multivariate statistics. This approach revealed other interesting variations in the parietal profile (Bruner 2004, 2008; Bruner, Manzi, and Arsuaga 2003). In general, nonmodern humans display a relevant allometric component in endocranial variation, and a large percentage of the shape differences are related to variations in size. Thus, when the brain becomes bigger, its geometry changes according to the existing structural network, arranging the skull versus brain functional requirements. Neanderthal endocranial morphology (i.e., the most encephalized nonmodern taxon) is largely the result of this allometric pattern. However, two aspects are worthy of note. First, the *Homo* allometric variation involves a relative shortening and flattening of the parietal profile, and Neanderthals show the maximum expression of this pattern. In this species, this endocranial morphology is interestingly associated with parieto-occipital additional ossification centers, suggesting a sort of “morphological instability” of the upper-posterior vault structures (Sergi 1948). Second, Neanderthals display a nonallometric lateral enlargement of the upper parietal volumes, leading to their classical *en bombe* profile when viewed from the rear.

Conversely, modern humans depart from the general allometric trajectory of the human genus because of their de-

finite enlargement of the whole parietal surfaces, both laterally (as Neanderthals) and along the midsagittal and vertical directions. A similar situation is also evident when taking the ectocranial profile into account (Bruner et al. 2004). This brain reorganization is in some way associated with convolution of the entire brain structure (Bruner 2004) and with the globularity of the modern neurocranium recognized as an autapomorphy of *Homo sapiens* (Lieberman, McBratney, and Krovitz 2002). Additionally, modern humans have been shown definitely to have more complex vascular traces on the endocranial surface, particularly reticulated and developed at the parietal surface (Bruner and Sherkat 2008; Bruner et al. 2005). This may be associated with an increased vascular network or with differences in soft-hard tissue relationships that consequently generate more imprints (Bruner, Mantini, and Ripani 2009). In the first case, it must be intended as a physiological adaptation and in the second case as a structural consequence. Nonetheless, in both cases the vascular system also supports a certain level of morphological reorganization in the parietal areas of the modern human endocasts. Figure 1 shows the human taxa for which paleoneurological information are sufficiently available with their supposed species-specific changes.

## Parietal Shape and Form Differences between Endocasts of Different Human Taxa

Naturally, geometrical changes in the parietal morphology can be achieved through many different processes, either intrinsic (superficial or deeper layers of the parietal cortical volumes) or extrinsic (changes external to the parietal volume secondarily affecting the shape of the parietal morphology). To better evaluate the entity of these parietal differences, the following study presents a morphological comparison between three representative specimens in order to attempt to delineate the geometry of some sufficiently reliable and informative parietal landmarks. The specimens used in the present comparison are the endocast from Salé, La Chapelle-aux-Saints, and Vatte di Zambana. The skull from Salé was found in Morocco and dates back to about 500 ka (see Hublin 2002). It can be generally referred to as *Homo erectus* (*sensu lato*). Considering the lack of any derived features (even the occipital projection described for the Asian *H. erectus*; see Bruner 2004), this endocast could well represent the basic endocranial morphology of the genus *Homo*. The cranium from La Chapelle-aux-Saints represents one of the best known “classic” Neanderthals (see Schwartz and Tattersall 2002). The skull from Vatte di Zambana represents an anatomically modern human from northern Italy, and it dates back to 8 ka (Corrain, Graziati, and Leonardi 1976; Newell, Constandse-Westermann, and Meiklejohn 1979).

The configuration used here involves nine two-dimensional landmarks (fig. 2): the superior midsagittal and inferior fron-



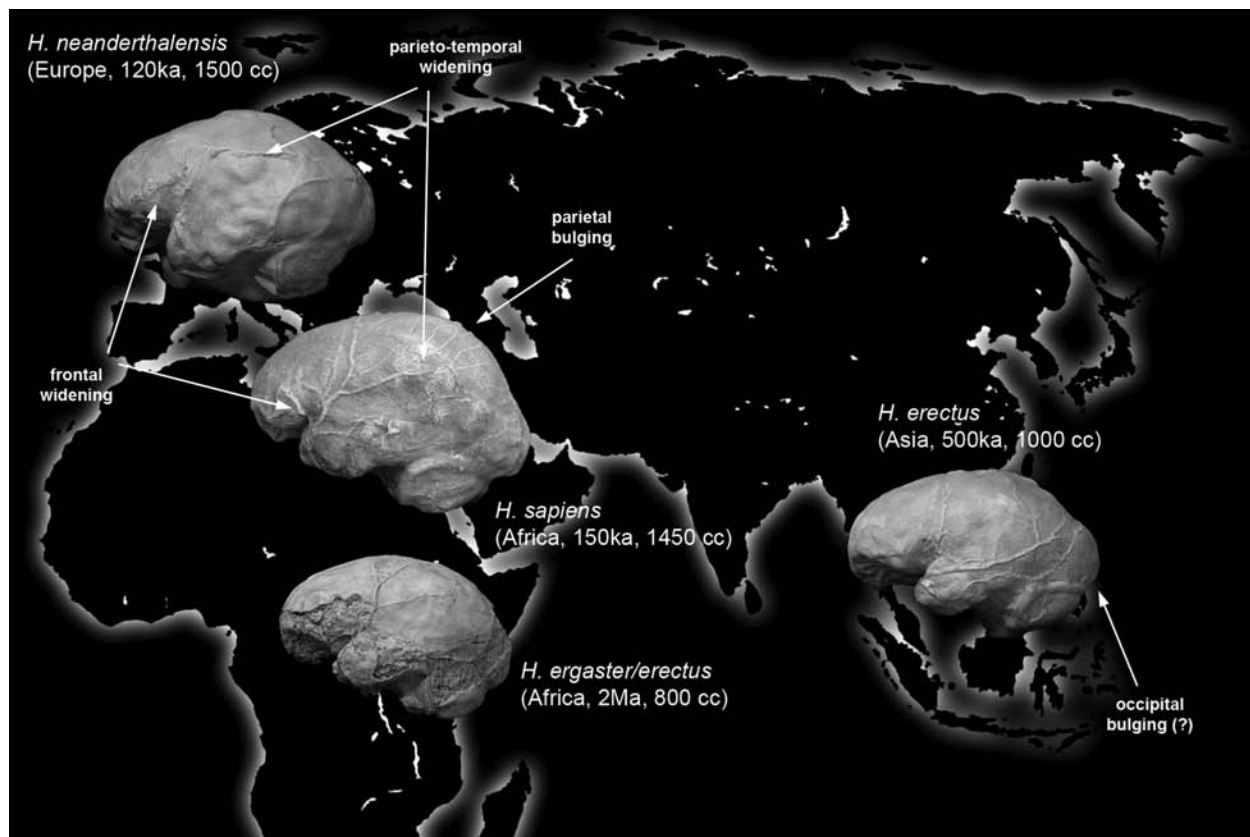


Figure 1. Main endocranial variation in the human genus. When compared with the most archaic African human species, Neanderthals and modern humans both display lateral widening of the parietal areas but associated with midsagittal flattening in the former group and bulging in the latter. Apart from these changes, the frontal lobes widen in both species (Bruner and Holloway 2010). Asian *Homo erectus* may show a certain bulging of the occipital poles (Bruner 2004). The endocasts show specimens representative of each taxon with their generic geographical and chronological origin (*Ma*, million years before present; *ka*, thousand years before present) and average cranial capacity (*cc*, cubic centimeters).

totemporo-parietal boundary of the central sulcus, the posterior end of the lateral sulcus, the midsagittal convergence of the postcentral sulcus, the perpendicular sulcus between the parietal and occipital areas, the midpoint between these last two landmarks (midparietal), the anterior edge of the intraparietal sulcus, the boss of the supramarginal gyrus, and the boss of the angular gyrus. Clearly, such traits are difficult to recognize in fossil endocasts. Most of them are perceivable as feeble grooves, and the recognition of such landmarks is logically based on experience and subjectivity. Nonetheless, this approach is the only one available to describe the anatomical variation in fossil species, and, although with proper caution, results can offer new and interesting perspectives. Two other landmarks were used as an endocranial baseline: the anteriormost point of the frontal lobes (frontal pole) and

the posteriormost point of the occipital lobes (occipital pole) along the axis of maximum hemispheric length.

Landmarks were sampled in three dimensions using a Microscribe 3DX (Immersion) on both hemispheres. Each specimen was sampled four times, and the average configuration was used to limit intraobserver error. The coordinates were aligned using the Procrustes registration, which translated all the configurations to a common centroid, scaled them to unitary centroid size, and finally rotated the coordinate systems, minimizing the residuals according to a least squares criterion (Bookstein 1991; Slice 2007). This approach makes it possible to standardize geometrical models, making them comparable and statistically congruent (for further details, see Zelditch et al. 2004). The configurations were aligned along the axis of maximum variation using *Morpheus et al.* (Slice

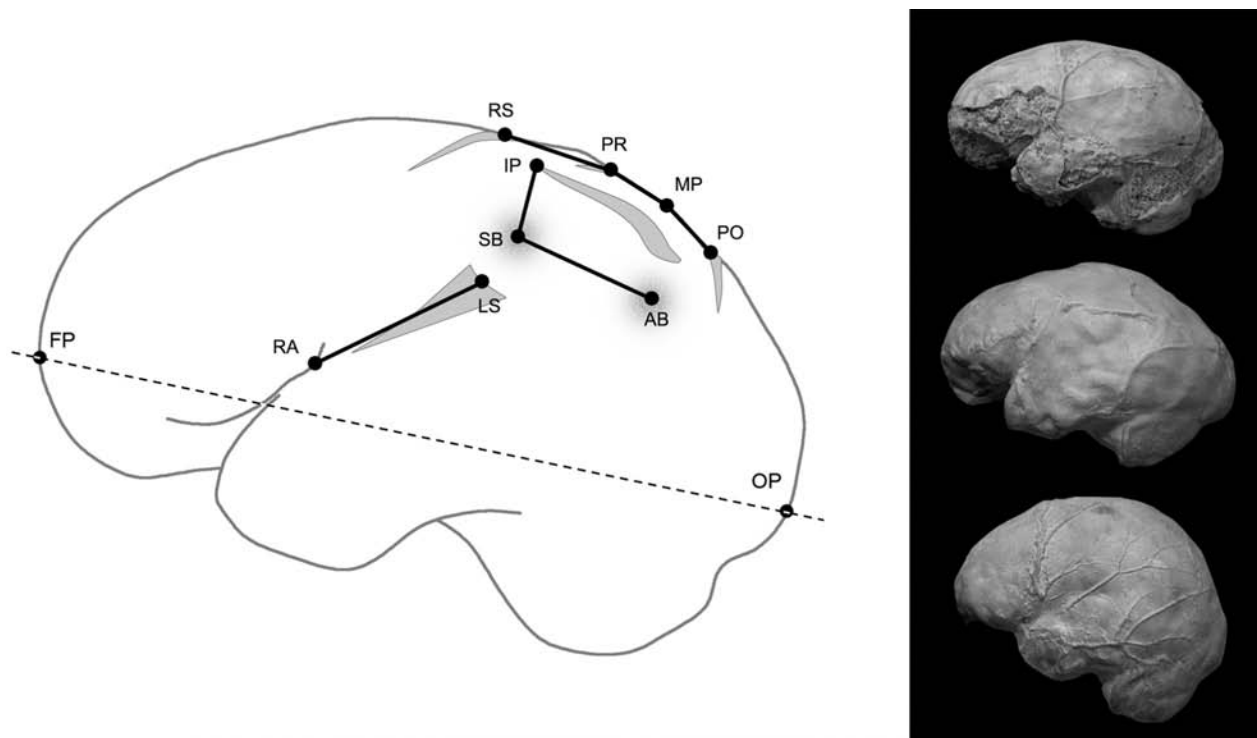


Figure 2. *Left*, configuration used in the present analysis. It includes two baseline points (*FP*, frontal pole; *OP*, occipital pole) and nine parietal landmarks, four on the midsagittal profile (*RS*, Rolandic sulcus; *PR*, post-Rolandic sulcus; *PO*, parieto-occipital sulcus; *MP*, midparietal point), three on the lateral surface (*IP*, anterior edge of the intraparietal sulcus; *SB*, supramarginal boss; *AB*, angular boss), and two localizing the lateral sulcus (*RA*, anterior edge of the Rolandic sulcus; *LS*, posterior edge of the lateral sulcus); see text for details. *Right*, the comparison was performed using the endocasts from Salé (*top*), La Chapelle-aux-Saints (*middle*), and Vatte di Zamabana (*bottom*).

2000). This passage also standardizes the orientation of the whole sample. Subsequently, the coordinates of the right hemisphere were eliminated, and the coordinates from the left hemisphere were flattened onto the *Y*-plane (i.e., in lateral view). Considering the parietal convolution described for modern humans, this approach is useful to better appreciate the changes in specific parietal subregions. The resulting two-dimensional configurations were then compared using the fronto-occipital baseline (from the frontal pole to the occipital pole) and the Procrustes superimposition (without the frontal and occipital poles).

Together with these direct geometric comparisons, the differences between the configurations were also visualized using thin-plate spline deformation grids (Bookstein 1991). These grids describe the minimum deformation required to transform one geometrical model into another, interpolating such deformations all along the surface. This approach makes it possible to visualize the overall spatial changes independently on the superimposition procedures.

The first set of comparisons was performed by aligning the

configurations to the same maximum hemispheric length (frontal pole–occipital pole); that is, differences are discussed in terms of form, size, and position of the parietal surface relative to this baseline. Compared to that from Salé, the modern endocast shows a definite enlargement of the parietal area (fig. 3*a*). This parietal enlargement is associated with volumetric changes of the areas that are superior to the supramarginal and angular bosses (namely, the upper parietal lobule, the intraparietal sulcus, and the upper part of the lower parietal circumvolutions). The enlargement is particularly evident at the center of this surface. The dilation of the upper parietal structures is associated with a geometrical compression at the postcentral area and around the lateral sulcus (i.e., at the supramarginal gyrus). The relative length and position of the lateral sulcus are not markedly different.

The deformation function can be pushed beyond the actual recorded magnitude. This mathematical exercise makes it possible to localize the surface points or areas that are particularly responsible for the dilation/compression pattern. Interestingly, variations in this deformation pattern from the modern

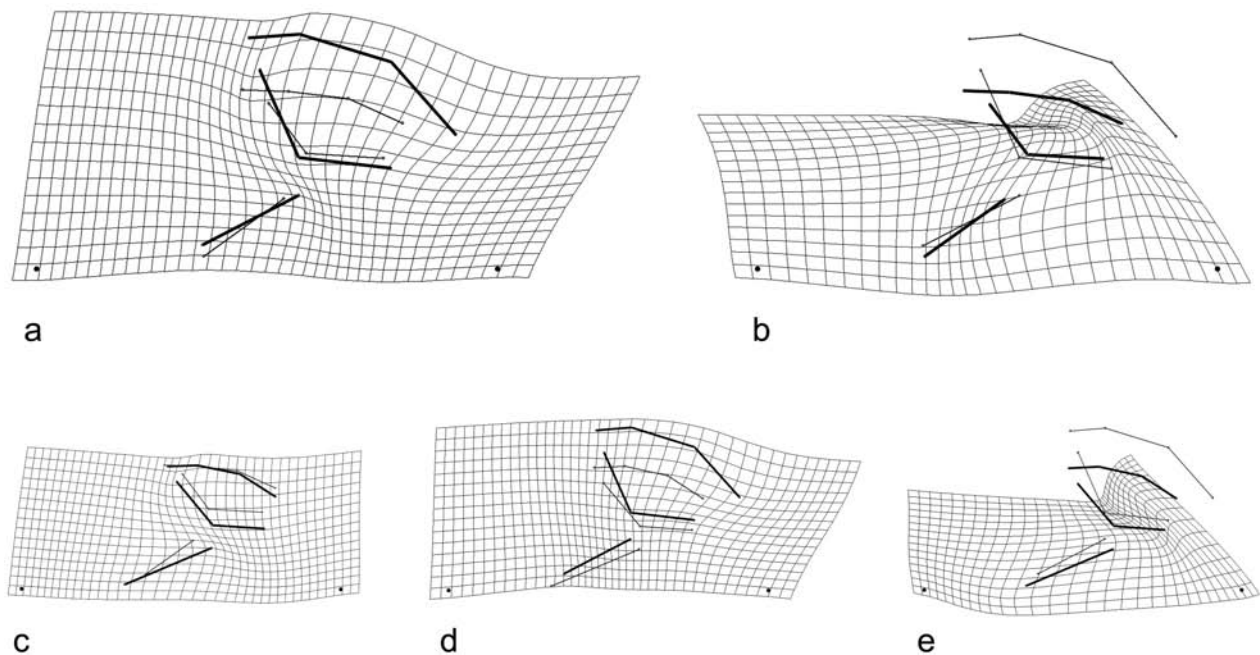


Figure 3. Baseline superimposition. The coordinates from the single endocasts are compared by superimposing the configurations on the same baseline (from frontal to occipital poles; *dots*). Therefore, differences are expressed according to the same hemispheric length. The thin-plate spline deformation grids display the spatial changes (*thin links*, reference form; *bold links*, target form). *a*, Salé versus Vatte di Zambana; *b*, Vatte di Zambana versus Salé ( $\times 1.6$ ; note the crease midway at the upper parietal area); *c*, Salé versus La Chapelle-aux-Saints; *d*, La Chapelle-aux-Saints versus Vatte di Zambana; and *e*, Vatte di Zambana versus La Chapelle-aux-Saints ( $\times 2.0$ ; note the crease at the upper parietal area).

endocast to the archaic endocast highlight a “crease” exactly midway within the above-mentioned upper area and around the intraparietal sulcus (fig. 3*b*). Creases are areas where the interpolant function “collapses” the neighboring space (Bookstein 2000). Although they are just mathematical by-products of the model involved, their position and sequence may reveal details of morphological differences or even underlying structural/functional properties (such as constraints or morphogenetic sources).

The comparison between Salé and La Chapelle-aux-Saint displays a different pattern in which there is again a relative enlargement of the upper parietal areas, but these are entirely directed downward (i.e., pushing the lower parietal surface and the lateral sulcus; fig. 3*c*). The comparison between the Neanderthal endocast and the modern endocast shows (in the latter) a general enlargement of the whole parietal surface, increasing from the lower to the upper areas (fig. 3*d*), and the reverse pattern leads again to a compression of the area around the intraparietal sulcus (fig. 3*e*).

The second set of comparisons includes only the parietal

landmarks (without the hemispheric baseline), superimposed according to the Procrustes procedure. Hence, shape differences between specimens are minimized, showing the changes in the morphology and position of the parietal configuration after size and location have been removed.

The comparison between the Salé endocast and the modern endocast stresses once more a generalized enlargement of the whole upper parietal volumes, with compression of the surface between the supramarginal gyrus and the lateral sulcus (fig. 4*a*). The reverse pattern, magnified beyond the effective difference, shows a crease in the uppermost area of the upper parietal lobules (fig. 4*b*). The differences between the Salé and Neanderthal endocasts remain the same as in the previous comparison but at a lower magnitude and with some further changes in the orientation of the lateral sulcus (fig. 4*c*). The comparison between the Neanderthal and modern endocasts (fig. 4*d*) and its reverse (fig. 4*e*) shows once more a generalized enlargement of the upper lobules in the second specimen, associated with a crease on the upper parietal surface.

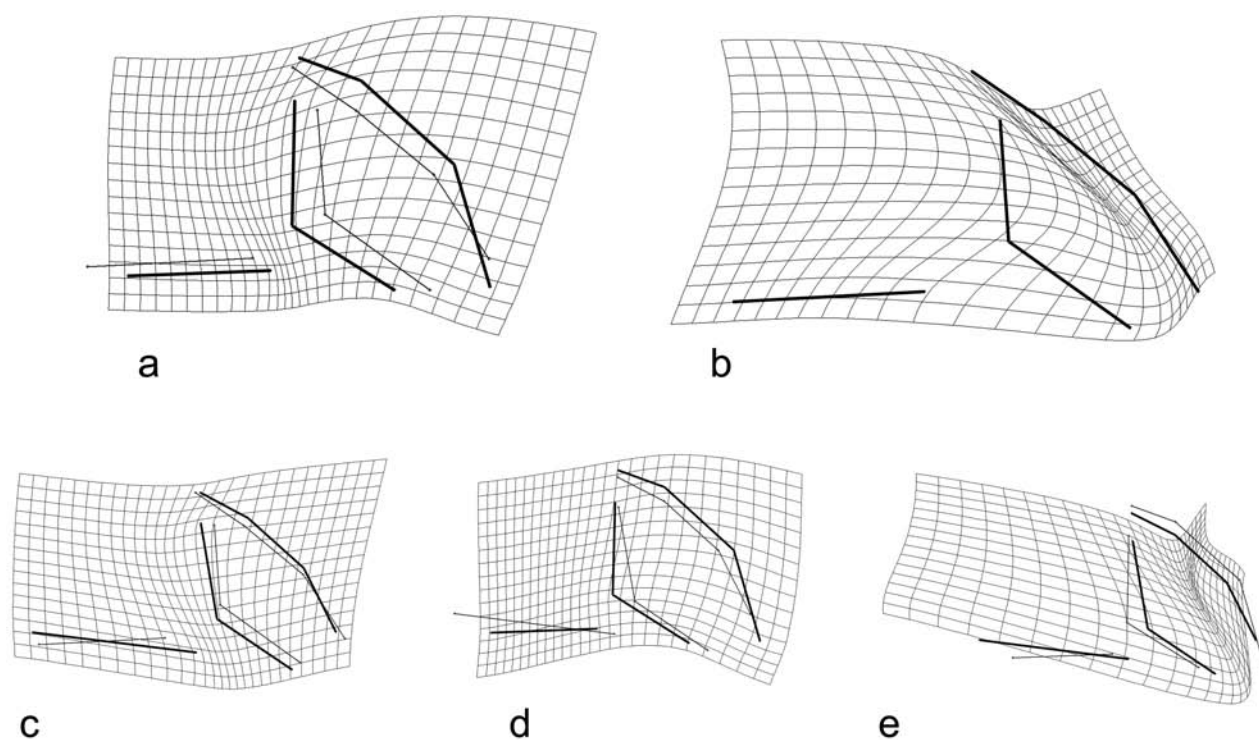


Figure 4. Procrustes superimposition. The coordinates from the single endocrasts are compared by superimposing the configurations through the Procrustes registration. Therefore, differences between the parietal shapes are minimized. The thin-plate spline deformation grids display the spatial changes (*thin links*, reference form; *bold links*, target form). *a*, Salé versus Vatte di Zambana; *b*, Vatte di Zambana versus Salé ( $\times 1.6$ ; note the crease midway at the upper parietal area); *c*, Salé versus La Chapelle-aux-Saints; *d*, La Chapelle-aux-Saints versus Vatte di Zambana; and *e*, Vatte di Zambana versus La Chapelle-aux-Saints ( $\times 3.0$ ; note the crease at the upper parietal area).

## Upper Parietal Areas: A Neurofunctional Synthesis

The analysis of the general endocranial morphology suggests that modern humans depart from a nonmodern allometric trajectory mainly because of a definite parietal enlargement (Bruner 2004, 2008; Bruner, Manzi, and Arsuaga 2003). The position of the parietal areas is pivotal within the general brain architecture, acting as a bridge between the other districts and sensitive to structural constraints associated with their reduced possibility of endocranial morphological adjustments (Bruner 2004). The preliminary evidence presented here provides more information to better delineate this hypothesis, indicating that this change concerns mainly the upper parietal areas (including the intraparietal sulcus). The superior parietal lobule has been regarded historically as a general associative area. In a pioneer paper, Eidelberg and Galaburda (1984) moved beyond the description of the parietal structures as polymodal sensory integration areas, trying to describe the anatomical components underlying the parietal organization.

They recognized that the upper parietal areas are more homogeneous than the lower ones, with some major cyto-architectural differences at the occipito-parietal junction and at the intraparietal sulcus. The occipito-parietal surface shows gradual features between the two lobes, stressing the structural and functional continuity between these two regions. The intraparietal sulcus, on the other hand, shows discrete regions, marking a more definite boundary with the lower parietal areas. Some sexual differences have been described in the gray/white matter ratio, with females showing larger values for the right hemisphere (Nopoulos et al. 2000).

As for almost all the major cerebral districts, most of the historical information regarding the upper parietal areas came from the analysis of associated dysfunctions in pathological conditions. The most well-known parietal syndrome is the “neglect,” or the failure, to attend to stimuli located on the side of the body opposite the side affected by brain damage (Corbetta et al. 2005). Such problems occur in about 25%–30% of parietal injuries, and 90% of the cases are rep-

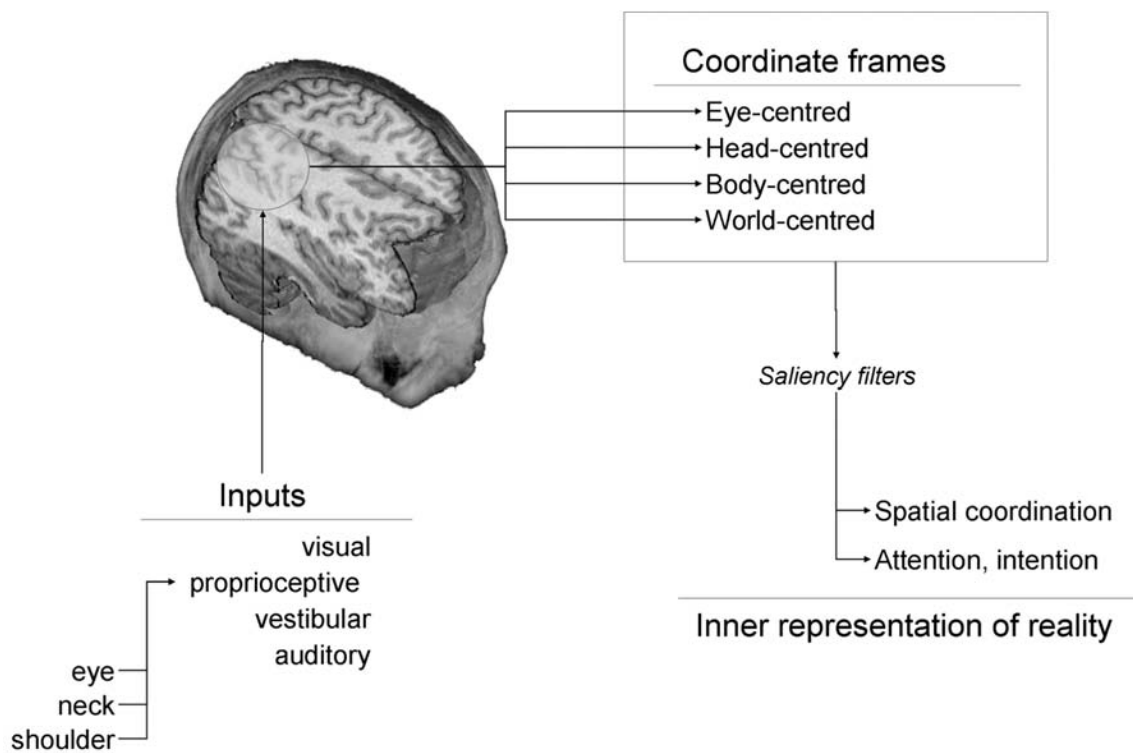


Figure 5. Upper parietal functional system. The diagram synthesizes the main upper parietal function. Spatial information from the inner and outer environments are coded in a common and integrated coordinate system that is used to perceive and manage the interaction between self and nonself structures (after a proper balancing of the relative importance of the single units).

resented by right-side injury, left-side spatial failure. Interestingly, this spatial deficit is associated with the upper parietal areas, but the injuries are often recorded at the lower parietal structures (supramarginal gyrus) or even at the upper temporal districts (Karnath, Ferber, and Himmelbach 2001). Hence, neglect can be hypothesized to be related to a structural dysfunction between the lower and upper parietal areas (Corbetta et al. 2005). Other pathologies frequently associated with the upper parietal structures include optic ataxia and directional hypokinesia (Battaglia-Mayer, Archambault, and Caminiti 2006). Optic ataxia is related to the failure to reach and grasp objects under visual control, with spatial and temporal alteration of movements to changing target location (mostly in a peripheral visual field). Generally, right-side damage affects the coordination of the left-side visual field (side effect), while left-side damage affects the coordination of the right hand (hand effect). Such impairments are probably related to a failure in the neural exchanges within the frontoparietal network of eye-hand coordination (Battaglia-Mayer and Caminiti 2002). Directional hypokinesia refers to the temporal elongation of hand reaction and movements. Parietal injuries generally affect the contralateral hand and arm

(Battaglia-Mayer et al. 2005). Another group of functional disorders is associated with an attentional deficit, and it is worth noting that the main problem in parietal patients is not focusing on a new target but disengaging attention from the previous one (Posner et al. 1984).

Apart from pathological dysfunctions, the first experimental data available showed that parietal areas were generally involved in sensory-motor integration, memory-induced repertoires, spatial constancy, direction and redirection of attention, and visually guided reaching and grasping (Mountcastle 1995). In other words, the functions of the upper parietal areas can be generally described as visuospatial integration and pragmatically divided into two (related) categories: (1) spatial coordination and representation and (2) attention and intention (fig. 5). Although the first is more associated with physical movements and the second with higher cognitive processes, they are in fact closely linked, being organized on the same neural networks.

The integration of body versus space coordination is the result of the continuity between the parietal lobe (superior areas) and the occipital lobe (extrastriate areas) and of the large corticocortical connectivity between the upper parietal

and prefrontal structures (Wise et al. 1997). Movements associated with reaching and grasping objects are the simplest examples of coordination between hand movement and eye position, computing distance, direction, velocity, and position of the planned movements (Battaglia-Mayer et al. 2000, 2003). Thus, reaching is the final result of the neural interaction between occipital areas (retinal signals) and frontoparietal feedbacks (spatial and intentional coordination), interfacing vision and movements (Ferraina et al. 1997). Such parietal spatial mapping is not associated with a defined neural surface (as in the retinotopic coordinates), but it is probably the result of nonlinear transformations between parallel circuits (Pouget and Sejnowsky 1997). The resulting reference frame is not constant, but it is dependent on the context (Battaglia-Mayer et al. 2001).

This integration is based on proprioception, vision, gaze, and attention (involving preparation and execution of movements). Hence, the upper parietal areas combine the information from the intrinsic spatial organization (the body) with the outer spatial geometry. This process requires a constant exchange between body-centered and world-centered coordinates, integrating different sensorial inputs (auditory, visual, velocity, position) in different coordinate frames (eye, head, body), possibly represented in different networks and providing a “holistic impression of space” that involves awareness and abstract representations (Andersen et al. 1997). Parietal neurons have been demonstrated to be activated when the individual “had a mind” to deal with an external stimulus, visually or through movement, suggesting that the parietal lobe system “forms a neural image of surrounding space” (Mountcastle 1995:389).

The second general level of visuospatial integration concerns the preliminary and preparatory neural activities that lead to the interaction between the body and the spatial framework, that is, attention and intention. In fact, the multisensory integration of the upper parietal areas is directly involved in the formation of intention and cognitive plans through spatial attention and awareness (Andersen and Buneo 2002). Interestingly, the representation of space, goal direction, and orientation of attention are part of a selective process that depends on the current sensorial context: each object included in the spatial coordinate frame has a saliency depending on intrinsic (associated with the object) and extrinsic (associated with the personal history of the subject) properties (Wardak, Ben Hamed, and Duhamel 2005). Such selective perception of reality is associated with neural activities of the intraparietal sulcus, leading to the production of “saliency maps” of the perceived physical environment (Gottlieb, Kusunoki, and Goldberg 1998). Therefore, the representation and interaction of the spatial frameworks is dependent on personal experiences associated with behavioral relevance and meaning of the stimuli (Freedman and Assad 2006). This framework generates intentions, which naturally represent abstract thinking, initially coded in visual coordinates and then transformed through decision making (competition between potential

movements) and motor attention (Andersen and Buneo 2002). Different neural surfaces may be responsible for different attentional processes (Yantis et al. 2001), but the intraparietal sulcus is the brain structure principally involved in the attentional and intentional management (Bisley and Goldberg 2003; Freedman and Assad 2006; Rushworth, Paus, and Sipila 2001).

A final note concerns the functional relationship between parietal lobes and numerical processing. Actually, the mapping functions associated with these cortical structures are not limited to the management of the physical space and interaction between physical elements but also when handling conceptual issues such as those related to computation: non-symbolic and symbolic elements are linked by the integration at the intraparietal sulcus between repeated stimuli and the mental tools of the internal representations, leading to ordered coordination of numerical information (Ansari 2008; Cantlon et al. 2006).

## Human Brain Evolution and the Frontoparietal Network

The upper parietal areas are involved in a neural network formed together with the occipital and frontal lobes (fig. 6). As mentioned, the occipital areas are rather continuous with the parietal surface in terms of function, structure, and cytoarchitecture. It is worth noting that in human evolution, the occipital and parietal bones also have been hypothesized to be part of a single structural unit and flattening of one part is associated with bulging of the other (Gunz and Harvati 2007).

Apart from the spatial and functional contiguity with the occipital lobe, the posterior parietal cortex is linked by strong corticocortical projections with the prefrontal cortex. The coordination between eye and hand movements is the result of recursive processes between these two functional areas matching vision and movements (Marconi et al. 2001). In general, the frontoparietal network involves a progressive match of information by recursive signaling through ipsilateral projections and intrinsic connectivity (Battaglia-Mayer, Archambault, and Caminiti 2006; Battaglia-Mayer and Caminiti 2002). The inferior parietal lobule is mainly connected with the dorsolateral prefrontal surface, while the upper parietal lobule is mainly connected with the dorsomedial prefrontal cortex (Wise et al. 1997). This strong relationship between the parietal cortex and the prefrontal cortex is also evidenced by matched patterns of neural activities during working-memory tasks (Chaffee and Goldman-Rakic 1998). Information such as that regarding distance and direction of movements is related to separated and parallel working-memory buffers, with the former decaying faster, showing smaller errors, and longer programming (Battaglia-Meyer et al. 2003).

Such considerations must be taken into account carefully not only when the upper parietal functions are discussed *per se* but also when general properties such as working memory

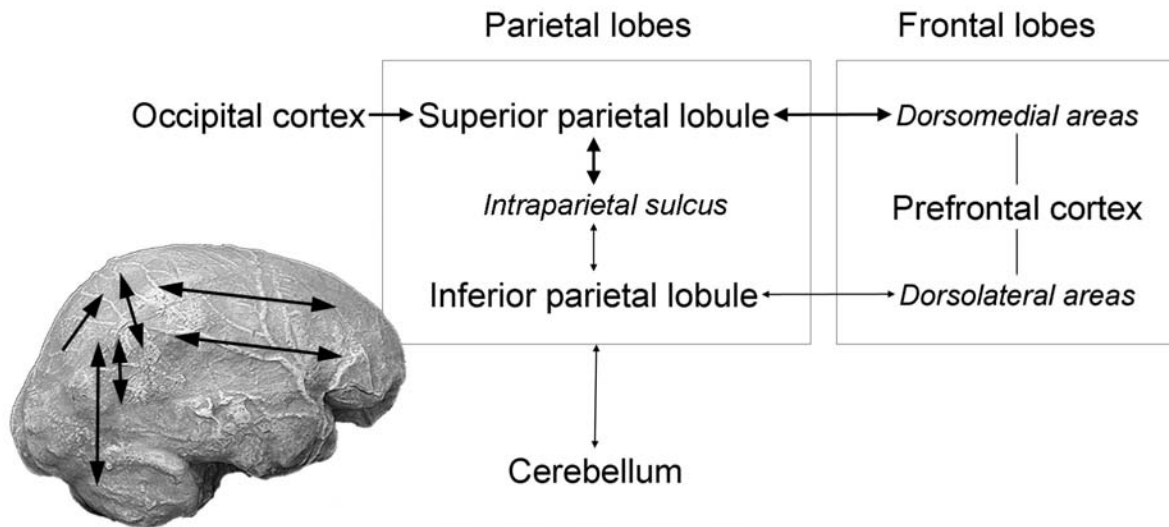


Figure 6. Upper parietal network. The diagram synthesizes the main upper parietal connections. There is a definite continuity between the occipital and parietal lobes. The intraparietal sulcus is the more distinctive component of the upper parietal areas in terms of both cytoarchitecture and neural functions. A large set of connections provides a complex frontoparietal network. Interaction with the cerebellar lobes merits further attention.

are hypothesized to play a major role within the cognitive organization of modern humans (Wynn and Coolidge 2003, 2006). When we are dealing with the upper parietal volumes, we are directly involved in the visuospatial sketch pad described as a relevant component of Baddeley's working-memory model (see Coolidge and Wynn 2005). At the same time, the upper parietal lobules are directly in contact with the lower parietal lobule (associated with the phonological storage of the Baddeley's representation) and strongly interconnected with the prefrontal (dorsal) areas (supposed to be somehow related to the central executive functions). Hence, the upper parietal lobes can easily represent a sort of center of gravity for the working-memory networks. For sure, the capability to organize the external reality within a personal framework through "virtual" handling of its parts is a requisite needed to dissect a final target into subgoals (Beaman 2010) or to evolve a conjunctive/additive technology from a reductive/subtractive approach (Ambrose 2001). As a matter of fact, the working-memory literature is largely based on terms dealing with visuospatial integration and functions associated with the upper parietal areas, such as "reordering of elements," "internal mental images," "internal mental representation," "imagined world," "thought experiment," "orienting attention," and "abstract representation" (see the many examples in this volume).

It must be shown that such mental abilities are well represented by the six-subsystem model proposed by Barnard and colleagues (Barnard et al. 2007), in which a new spatial-praxic subsystem interacts with a general multimodal sub-

system. They recognize the relevance for the working-memory model of such hypothetical change because of the direct involvement of the visuospatial sketch pad. The spatial-praxic subsystem allows internal mental imagery concurrently with the control of action, mental manipulation of the information, and abstract organization of the reality. They hypothesize that this organization is also present in the mental architecture of the great apes and has possibly already evolved in the last common ancestor between humans and apes. If this is true, we can speculate whether the morphological changes at the upper parietal areas in modern humans have been associated with a further exploitation of this cognitive network basically shared with the other hominoid taxa.

Recently, the strong functional connection between the frontal and parietal areas has also provided the basis to develop interesting models to investigate the behavioral responses in terms of general intelligence. The frontoparietal integration has been hypothesized to be the main pacemaker of the complex network underlying the higher human mental aptitudes (Jung and Haier 2007), with the posterior parietal areas directly involved in the reasoning abilities (Lee et al. 2006). It is worth noting that the two human species showing parietal enlargements (i.e., modern humans and Neanderthals) also display a definite widening of the anterior cranial fossa, housing the prefrontal volumes (Bruner and Holloway 2010).

It is also worth mentioning that the cerebellar lobes may have a further role in transforming and integrating parietal information (Wise et al. 1997). Unfortunately, the paleoneu-

rological information on the morphological variability of the cerebellar areas is still too fragmented to support useful hypotheses on this issue.

## Parietal Evolution: Some Final Remarks

The morphological variations described in the fossil record must be necessarily related to the natural and cultural environments associated with human phylogeny. Concerning the human natural history, the integration between the occipital and parietal functions is relevant to all primate evolution, being related to binocular vision and visual predation (Sakata et al. 1997). Neurofunctional evidence and geometric comparison of the parietal surface suggest that the intraparietal sulcus should be carefully considered when the evolution of modern human cognitive features is investigated. This area is the most distinctive in terms of cytoarchitecture, with some evident differences between human and nonhuman primates (Eidelberg and Galaburda 1984). It is generally connected to the postcentral sulcus (about 75% of the cases), without recognized differences between sexes or hemispheres (Ebeling and Steinmetz 1995). The spatial properties associated with this area are also related to the discrimination of objects or single parts of them (Faillenot, Decety, and Jeannerod 1999). The intraparietal sulcus displays a finer functional division, accounting for different cytoarchitectonic and functional districts (Choi et al. 2006). It represents a relevant percentage of the cortical parietal surface, with a remarkable depth between 13 and 26 mm (Ebeling and Steinmetz 1995). Considering that about two-thirds of the parietal surface is included within the cortical sulci (Marshall and Magoun 1998), the possibility that relevant evolutionary changes may have occurred within the folded cortex is quite high.

Unfortunately, the comparative information concerning the neurofunctional homology in primates for these parietal structures is still fragmentary and incomplete, hampering a robust reconstruction of the general phylogenetic framework. Some aspects of general organization of the parietal structures are supposed to be very conservative within this group (Culham and Kanwisher 2001; Rushworth, Paus, and Sipila 2001; Sereno, Pitzalis, and Martinez 2001). Although neural components are sometimes difficult to compare because of their uncertain origin and homology, early studies had already shown possible discrete differences in the human parietal cortex (Posner et al. 1984). It is now clear that the human intraparietal sulcus contains areas that are not present in nonhuman primates (Orban et al. 2006; Vanduffel et al. 2002), providing the basis for an interesting period of new researches in this direction.

Apart from the comparative context, anatomical evidence and neurofunctional data must be properly integrated with the archaeological information to support complete evolutionary hypotheses (Malafouris and Renfrew 2008). In this framework, it is even more interesting that tool making has been associated with the frontoparietal perceptual motor sys-

tem through the left-dominant activation of the dorsal part of the intraparietal sulcus (Stout and Chaminade 2007; Stout et al. 2000). Actually, in terms of handling, the spatial selection tasks of the superior parietal lobule are directly linked to the contralateral finger movements (Shibata and Ioannides 2001). However, most of all, lithic production—and even more, art (“parietal” art, a nice coincidence!)—require the integration of visuospatial information, the introduction of geometrical concepts into the cultural system, and the ordering and repetition of modular motor sequences (Hodgson 2006). Actually, the supposed symmetry of Acheulean tools may have involved a reorganization of the visuospatial integration features (Hodgson 2005).

The functional meaning of the visuospatial integration processes and the morphological evidence from the paleoneurological record strongly support a fundamental evolutionary role of the upper parietal lobule. The most exciting challenge is now to localize chronologically such neural changes and check whether the modern human lineage evolved together with a modern human brain (Bruner 2010).

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# Making Friends, Making Tools, and Making Symbols

by Matt J. Rossano

Using Peircian semiotics as an interpretive framework, I evaluate the archaeological evidence for the emergence of symbolism in hominin evolution. While this framework would predict a progression from icons to indexes to symbols, the archaeological record is unclear as to whether icons or indexes are primary. Symbols, however, do appear to be late arriving, confirming the prediction that symbol learning is cognitively demanding. I argue that developmental and social factors were critical in the evolutionary emergence of symbolism. The role of enhanced working memory in the emergence of symbolism was most likely in giving the *Homo sapiens* brain the ability to support complex symbol systems such as language.

## Introduction

This paper is divided into two sections. In the first section, I use the semiotic theory of philosopher Charles Sanders Peirce (1978 [1931]) as a framework for evaluating the emergence of symbolism in the hominin archaeological record. In the second section, I attempt to identify the important selective factors giving rise to symbolism in hominins and the role that enhanced working memory may have played in this evolution. Overall, the following conclusions are drawn. (1) It is unclear whether iconic or indexical artifacts are primary in the archaeological record. (2) Both iconic and indexical artifacts are present sometime between 500,000 and 100,000 years before present (ybp) in the form of pigment use, imposed form on tools, composite tools, and beads. (3) True symbols (in the Peircian sense) emerge very late in the form of decorative items, abstract figurines, and cave art. (4) Adult symbol learning may be prohibitively challenging, thus requiring that symbol acquisition be carried out early in development when certain cognitive limitations actually make its acquisition more feasible. (5) The emergence of iconic and indexical artifacts roughly corresponds with an enlargement of the hominin brain, suggesting that the increased immaturity of hominin offspring facilitated this cognitive advance. (6) An enhancement of working-memory capacity was probably not essential in establishing symbolic function in hominins, but it may have been critical in permitting *Homo sapiens* to acquire highly complex symbol systems (such as modern

language). (7) Social factors such as a secure and stable domestic environment and increasingly demanding social rituals were key selection factors in the enhancement of working-memory capacity.

## Peircian Semiotics

One of the most thorough examinations of semiotics (the study of signs and symbols) comes from philosopher C. S. Peirce (1978 [1931]). Peirce defined three levels of reference: iconic, indexical, and symbolic. Iconic signs are ones that bear a perceptual or physical resemblance to the things they signify, such as a round pebble being used to represent a soccer ball. Indexical signs are ones that indicate (as the name implies) the presence of what they signify based on a temporal or spatial association. For example, a weather vane indicates the wind (when the wind blows, the vane moves), tears indicate sadness, smoke indicates fire, and so on.

While both iconic and indexical signs can be thought of as “symbolic” in the sense that one thing is standing for another, Peirce reserves the term “symbol” for only those occasions where the relationship between the signifier and the signified is purely arbitrary. For example, the dollar sign (\$) is truly symbolic because its relationship to money is based solely on convention. The dollar sign does not resemble real currency (and therefore is not connected iconically to it), and it occurs only rarely in temporal or spatial proximity to currency (and therefore is not connected indexically to it). While these levels of reference are distinguishable, they are not necessarily mutually exclusive. A sign can sometimes overlap levels of reference. A smiley face looks like a smiling face but can also indicate happiness or the intention of conveying a joke (as is the case with electronic messages).

**Matt J. Rossano** is Professor and Department Head of Psychology at Southeastern Louisiana University (Department of Psychology, Box 10831, Southeastern Louisiana University, Hammond, Louisiana 70402 U.S.A. [mrossano@selu.edu]).

### *Cognitive Requirements of Referential Thinking*

Peirce (1978 [1931]) observed that the evolution of written language appeared to progress from icons to more purely symbolic representations. This led him to argue that interpreting signs progresses hierarchically. To interpret indexes, one must understand icons. To interpret symbols, one must understand indexes. In this way, higher levels of reference (symbols, indexes) are built up from lower levels (indexes, icons). For example, understanding that smoke serves as an index of (indicator of) fire requires that one recognize (iconically) how a current experience of smoke is related to past experiences of it, very likely based on visual and olfactory resemblance cues. Furthermore, one must then associate this iconically based set of common experiences with the consistent presence of another stimulus: fire. Thus, iconic relationships cue a set of past experiences that then lead to an indexical association (“Gee, every time I see and smell X, Y is there, too”).

In a similar fashion, symbolic relationships are built on indexical ones. The temporal/spatial relationships that form the basis of indexes provide the scaffolding or foundation on which purely conventional associations can be constructed. Thus, in children’s word learning, concrete nouns (“dog,” “ball,” “mommy”) typically compose the largest single category of their initial vocabulary (Nelson 1973). Very quickly, though, it is not so much what words refer to (point to or indicate) in the real world that drives vocabulary learning but how they relate grammatically and semantically to other words (Taylor and Gelman 1988, 1989). Or, put another way, while word learning may get started indexically (based on a word-object association), it does not really take off until it switches to a symbol-symbol-based reference system.

All of this raises the possibility that the human mind, with its full-blown capacity for (Peircian) symbolism, was preceded by hominin minds capable of less sophisticated forms of referential thinking (iconic and indexical). There is reason to suspect that this might be the case. Studies of ape language learning and language development in humans show that in both cases there is progression from an initial indexical phase to one of symbolic understanding (see discussion in Deacon 1997:85–92, 135–142). Thus, we might expect that the emergence of fully symbolic artifacts in the archaeological record would be preceded by iconic and indexical ones, providing evidence for the existence of these presymbolic hominin minds.

### *Crossing the Symbolic Threshold*

The purely arbitrary nature of symbolic associations makes them especially taxing to acquire. Neuroscience studies show that a broad network of neocortical structures is necessary for the acquisition of the purely arbitrary associations required when learning symbols (Asaad, Rainer, and Miller 1998; Chee et al. 2000; Eacott and Gaffan 1992). These structures

include the inferior temporal cortex, the dorsolateral prefrontal cortex, and the uncinate fascicles connecting the two. Furthermore, unless one is a human child, acquiring and using symbols is laborious and unnatural. Ape language studies have typically required hundreds, sometimes thousands, of repetitive trials in order to train subjects to use languagelike symbols (Greenfield and Savage-Rumbaugh 1990; Savage-Rumbaugh, Rumbaugh, and Boysen 1978). In one well-known study, two chimpanzee subjects—Austin and Sherman—had to be explicitly trained in what their linguistic symbols (lexigrams) *did not* refer to in order to make their language learning feasible.

There are two major challenges that must be overcome in acquiring symbols. First, unlike icons or indexes, symbol learning has little to no contextual support. An icon, by virtue of its appearance, cues its referent. An index also cues its referent by virtue of repeated temporal or spatial co-occurrence. Symbols, however, neither look like nor are temporally or spatially associated with their referent. Indeed, with some symbols, such as the word “angel” or the good-luck horseshoe above my door, no tangible referent is even possible. Thus, unlike icons or indexes, symbols provide little or no cuing support for their referents.

Second, what a symbol refers to is only partially based on the (already arbitrary and uncued) symbol-referent connection. Often, an even more important determinant for a symbol’s referent is the complex relationship the symbol has to other symbols in the context of its use. For example, in the context of “the boy who cried wolf,” the word “wolf” refers to a dangerous member of the canine family. In the context of hearing my wife’s assessment of her sister’s latest boyfriend, “He’s a wolf in sheep’s clothing,” “wolf” refers to a slick operator, a pretending opportunist looking for an easy victim. With symbols, it is often how the symbol relates to other symbols that determines its referent. This property does not apply just to linguistic symbols. In the context of a low-slung tool belt, a cheap cigar, and a worn-out New York Yankees cap, the dollar sign most likely means “cash only.” In the context of classical music and caviar, it most likely means “American Express Platinum.”

There is, however, an important caveat to the apparent difficulties of symbol learning. It could be that these difficulties make it especially hard for *adults* to acquire symbols, so much so that any potential adaptive advantage would be lost by the amount of effort and energy required to achieve the skill. In contrast to those of adults, children’s immature brains may actually have an advantage in acquiring symbols by virtue of their inability to keep track of the many possible object-to-symbol indexical relationships. This capacity limitation produces a strong preference for processing more global, higher-order, symbol-to-symbol relations at the expense of gaining a complete grasp of the symbol’s external referent. In this way, very young children may naturally fall into a learning strategy advantageous for acquiring symbol systems such as language (Elman 1993, 1999; Newport 1990).

For example, many very young children understand where and how to use the word “please” before they fully grasp its meaning. They recognize that it fits in with other (linguistic) symbols (such as those that request things) under certain conditions (such as when communicating with adults). Focusing exclusively on how it works within the larger system not only is practical (it gets you things) but also may be necessary, given the cognitive limitations of young children’s minds. This “advantageous limitation” may help to explain why human language learning is characterized by a critical period in early childhood and why Kanzi—the most celebrated ape language learner—acquired his linguistic skills so effortlessly relative to other (generally older) ape subjects.

### *Iconic Artifacts*

Given the hierarchical nature of referential cognition, we might expect that evidence of iconic artifacts is primary in the archaeological record, followed by indexes and symbols. Indeed, some researchers have argued for just such a sequence (see, e.g., Bednarik 2003 and comment by Bowyer [2003]). There is some indication that this might be true. Evidence of red ochre and other mineral pigments dates as far back as 300,000 ybp in the hominin archaeological record (Barham 2002; Clark and Brown 2001). Barham (2002), for example, has unearthed more than 300 pieces of variously colored mineral pigments dated anywhere from 270,000 to 170,000 ybp from the Twin Rivers site in Zambia. The pigments appear to have been intentionally transported to the site from remote locations and show evidence of deliberate modification. Although red ochre and other mineral pigments can have utilitarian uses (Bahn and Vertut 1988; Keeley 1980), evidence from many of these finds suggests ritual rather than practical use (Knight, Power, and Watts 1995; Watts 2002). Barham (2002:187) notes that the wide variety of different pigments found at the Twin Rivers site argues against purely practical use.

If mineral pigments had ritual meaning, what was it? Our hominin ancestors’ earliest use of pigments, according to Kuhn and Stiner (2007b:46), was probably to enhance or alter physical appearance—making the wearer more dramatic, impressive, or intimidating—as is not uncommon in contemporary traditional societies. Using archaeological and anthropological data, Knight, Power, and Watts (1995) have proposed a somewhat different function for early pigments, especially red ochre. In their view, red ochre would have signified menstrual blood and the fertility associated with it. Common to both these views is the notion that the pigment’s meaning would have been closely tied to perceptual appearance—either the appearance of the pigment itself (as blood) or the appearance of what it enhances (facial expressions, bodily contours, etc.). All of this suggests that where ritual use of mineral pigments appears likely from the archaeological record, its reference value was iconic in nature. In other words, it stood for things by virtue of perceptual cuing.

Pigment use may not be the only example of early iconicity in the archaeological record. Two Late-Lower/Early-Middle Paleolithic artifacts—the Berekhat Ram and Tan-Tan figurines—are noteworthy in that they appear to have been intentionally worked by hominins to enhance their natural anthropomorphic quality. The Berekhat Ram figurine is from the Golan Heights and dates to around 233,000 ybp, while the Tan-Tan artifact was found by the Draa River near the Algerian town of Tan-Tan and is dated to around 400,000 ybp (Bednarik 2003; d’Errico and Nowell 2000). The singularity of these finds warrants caution in their interpretation; however, if there is any meaning to them at all, it would likely be iconic.

### *Indexical Artifacts*

The primacy of iconicity in the archaeological record is challenged somewhat by stone tools. The earliest tools emerge well before any iconic artifacts and, according to Byers (1994), may represent natural indexes of their uses. In other words, a sharp edge indicates cutting, an arrowhead indicates hunting, and so on. Their indexical quality stands independent of whether or not one can firmly establish the toolmaker’s intentions in creating the tool. Thus, over time, one edge may end up being useful only for scraping while another may end up being useful only for slicing—these uses being primarily determined by the stone itself and its pattern of wear, not by what the toolmaker had in mind when he or she originally knapped it. So even though the toolmaker may never have set out to create “scrapers” and “slicers,” the “scraper” edge indicates scraping, and the “slicer” edge indicates slicing.

This logic, however, is not universally accepted. One problem is that it is partially based on the Gibsonian theoretical notion of *affordances*, in which an object’s uses are thought to be directly perceivable to the observer. However, the extent to which the Gibsonian approach can be successfully applied to hominin tool use is unclear (see, e.g., Davidson and Noble 1989). Moreover, it is doubtful that early hominins possessed a conceptual understanding of simple Oldowan edges as “tools” (as opposed to merely bodily extensions for achieving certain ends). In all likelihood, the conceptual category “tool” did not emerge until the advent of the Acheulean handaxe (see Coolidge and Wynn 2009:112).

Less controversial is the idea that an imposed form on a tool or the style of a tool can be used as evidence of the tool’s indexical nature. Chase (1991), following Sackett (1982, 1986), argues that where we can identify style in artifacts—that is, a consistent material patterning that cannot be attributed to the constraints of raw materials or artifact function—then that style serves as an index of the people who made the artifacts. Borrowing Chase’s (1991:198) example, if one group traditionally creates stools with three legs and another with four, then the number of legs on the remains of stools serves as a reliable indicator of a particular group.

However, identifying imposed form or style can be com-

plicated. For example, some have argued that late Acheulean handaxes (500,000 ybp) show a degree of symmetry and attention to form indicative of the toolmaker having followed a mental image of the desired finished product (Mithen 2006: 188; Wynn 2002). Additionally, Schick and Toth (1993: 282–283) contend that by around 300,000 ybp, regionally variant handaxe styles had emerged. Others, however, contend that the final form of a handaxe is more parsimoniously explained as the result of resource availability and multiple re-sharpenings over the course of the tool's history (Jones 1979; McPherron 2000).

While raw material and functional constraints may explain some handaxes, contemporary studies of handaxe manufacture suggest that the presence of imposed form or style is not entirely illusory. A well-shaped handaxe is not an easy tool to make. Stephen Edwards, an experienced stone knapper, claims that many months of concerted effort would be required for one to reach a skill level comparable to late Acheulean handaxe makers (Edwards 2001:606). Additionally, Oakley (1981) describes two handaxes from England in which the stones were knapped so as to center fossilized shells preserved in them. The care and skill required to do this indicate that the toolmaker was well aware of the visual effect he or she was creating. All of this supports the hypothesis that at least in some cases, the imposition of form or style on a handaxe was not accidental. Instead, the handaxe was being appreciated as a social signal of the maker's skill and/or cultural identity. Kohn and Mithen (1999) have argued that handaxes may have served an important function in mate selection as an indicator of planning ability, motor skill, resourcefulness, aesthetic appreciation, and overall good genes.

Around this same time (300,000 ybp), the first evidence of composite tools also emerges (Ambrose 2001; McBrearty and Tryon 2006). As both Wadley (2010, in this issue; Wadley, Hodgskiss, and Grant 2009) and Ambrose (2001, 2010, in this issue) have pointed out, composite tools make special demands on the cognitive system. Composite tools are those in which multiple components (such as a point hafted to a handle or shaft using some binding material or adhesive) are assembled using a multistage process sometimes extending over hours or days. The assembly process requires planning a sequence of motor actions and monitoring the progress of each stage (Haidle 2010, in this issue). A distinct advantage would have gone to those toolmakers who during the course of the assembly process could read signs indicating the future viability of the tool. The viscosity of the adhesive, the feel of the point's fit to the shaft, and the sturdiness of the binding material may all have provided key indicators of the progress of the ongoing tool-construction process. If properly understood, these signs may have allowed for critical adjustments in the process leading to a better tool. Note how all these signs would have been in reference to a distant event—the future state of the tool.

Finally, beads and body adornments very likely qualify as another form of indexical artifact. In traditional (and even

modern) societies, the way people ornament themselves is often an indicator of their social affiliations, such as age cohort, ethnic group, and marital and/or economic status (Kuhn and Stiner 2007a). Recent finds push the emergence of beads to well into the African Middle Stone Age. Intentionally perforated shell beads dated to over 75,000 ybp have been unearthed from Blombos Cave in South Africa (Henshilwood et al. 2004), and even older shell beads (100,000–135,000 ybp) were found among artifacts uncovered from the Skhul site in Israel and Oued Djebbana in Algeria (Vanhaeren et al. 2006). Among contemporary !Kung hunter-gatherers, shell beads like these are often used as gifts, called *hxaro*, that reinforce reciprocal relations among different bands (Wiessner 1982). The fact that the Skhul and Oued Djebbana sites are remote from the seashore origin of these shells supports the notion that they were transported there, possible by trade and/or gift-giving networks.

What made the shells valuable, however, was what they represented when worn. Recently, Kuhn and Stiner (2007a) have argued that beads represent an important transition in social marking. While pigments applied to the body might be used to signal information about a person's social status or kin affiliation, Kuhn and Stiner point out that pigment signaling is greatly limited in terms of durability, transferability, standardization, and a host of other factors. Beads, on the other hand, overcome these limitations, thus providing a more effective means of communicating social information to “intimate strangers”—those familiar enough with the wearer to know the meaning of the signal (“She's the chief's daughter”) but not familiar enough to know the wearer personally. In the context of *hxaro* (!Kung gift-giving alliances), for instance, an abundance of beads signals a rich network of friends and allies beholden to the wearer—a cautionary note to potential rivals and something very difficult to convey using pigments.

If we take imposed form and/or style on handaxes, composite tools, and beads as the securest evidence of indexes, then collectively this evidence overlaps with the emergence of iconicity in the form of pigment use (a time frame running roughly from 500,000 to 100,000 ybp). The early portion of this time frame also corresponds to an increase in brain size marking the emergence of archaic *Homo sapiens* (Ruff, Trinkaus, and Holliday 1997). A larger hominin brain would have meant even more altricial offspring. Given that immature primate brains appear to have some advantages in associative learning, this increased altriciality may have actually facilitated the emergence of these new forms of referential thinking and laid the foundation for the capacity to acquire symbols.

## The Emergence of Symbolism

The elaborate burials, spectacular cave art, and highly imaginative imagery and artifacts from the Upper Paleolithic stand as singular achievements of modern *Homo sapiens*. While archaics such as Neanderthals made use of beads and pig-

ments (d'Errico et al. 2003), they produced none of the decorative abstract remains that seem to demand a symbolic interpretation. Certainly, Upper Paleolithic art contains iconic and indexical elements; however, some of it also appears to be purely culturally defined (i.e., symbolic). Such items as the sorcerer image of Les Trois-Frères cave; the lion-headed man from Hohlenstein-Stadel; the circles, spirals, and other geometric forms found in Australian rock art; and the numerous mythic and therianthrope images of European cave art appear to possess elements that may be completely understandable only from within the cultural context of their creation.

Evidence cited earlier suggests that the move from index to symbol is not easy. Recently, Wynn, Coolidge, and Bright (2009) have provided an analysis of the cognitive requirements behind the creation of the Hohlenstein-Stadel artifact. They argue that the artisan needed to hold two disparate concepts (person and lion) in active attention while building an imagined superordinate category capable of uniting them (e.g., spiritual agent). It is precisely this sort of cognitive process—in which arbitrary connections must be made between sign and referent—that is central to symbol construction. The fact that abstract artifacts such as the Hohlenstein-Stadel appear relatively late in hominin evolution seems to reinforce the notion that symbol building is cognitively demanding.

The ability to hold disparate concepts in active attention and operate on them by building innovative connections places great demands on working memory. Indeed, Wynn and Coolidge (2007) argue that an enhancement of working-memory capacity was essential to the evolution of uniquely human cognition, including its powerful symbolic function. However, this enhancement is probably not a prerequisite for acquiring symbols per se—after all, apes have successfully learned rudimentary linguistic systems. Instead, an enhancement of working memory was probably more crucial in terms of the complexity of the symbolic system that the brain can support. The bonobo Kanzi learned to use a lexigram language system with relative ease (very likely aided by his early exposure). However, in stark contrast to human children, his language abilities have remained static at about the level of a three-year-old child, and short-term memory capacity has proven to be a major limiting factor (see Savage-Rumbaugh, Shanker, and Taylor 1998:69–73).

Enhanced working-memory capacity may have been critical in allowing *H. sapiens* to move from having limited symbolic potential to being symbol dependent—from protolanguage to syntactically and recursively complex language, from beads to abstract art. This transition may, in fact, be a requisite one for symbolism to provide any substantive fitness advantage. Until the brain is capable of supporting a level of symbolic complexity such that social life itself can be symbolically organized, then symbolism may be of only marginal consequence. What, then, were the selective factors behind this watershed transition?

### *Social Complexity and Cognitive Evolution*

That social pressure might be critical in human brain and cognitive evolution is becoming an increasingly prominent theme (Alexander 1989; Dunbar 2007; Geary 2005; Powell, Shennen, and Thomas 2009). Those of our ancestors who were best able to track social relationships, build strategic alliances, and make vital judgments about intentions and trustworthiness very likely gained a fitness advantage. Furthermore, a long tradition of psychological research has established the inferentially and computationally demanding nature of social cognition (Gilbert, Pelham, and Krull 1988; Heider 1958; Trope 1986). These demands are especially acute in executive functions such as attention, working memory, and cognitive control. One recent study has provided both correlational and experimental data supporting the notion that social engagement itself activates working memory and improves cognitive functioning (Ybarra et al. 2008). Thus, as the *H. sapiens* social world expanded and complexified, executive functions including working memory came under increasing pressure.

Archaic hominins, such as Neanderthals, were expert tool-makers and highly proficient hunters whose technical skills and behavioral competence differed little from their *H. sapiens* counterparts. The social worlds of archaics and *H. sapiens*, however, were quite distinct. Fossil evidence indicates that *H. sapiens* social groups were larger and more complex than those of Neanderthals. Relative to Neanderthals, European Cro-Magnon campsites are larger, more frequent, more intensely used and occupied, and (typically) more spatially structured (Bar-Yosef 2002; Dickson 1990:84–92, 180–189; Hoffecker 2002:129, 136; Stringer and Gamble 1993:154–158). Many of these sites show evidence of seasonal aggregation, larger population density, and other signs of social complexity and stratification (Mellars 1996; Vanhaeren and d'Errico 2005).

*Homo sapiens* groups were not just larger than those of Neanderthals; they were compositionally quite different as well. Increased longevity among *H. sapiens* meant that their groups were composed of considerably more older adults relative to young adults, adolescents, and children. Using dental samples, Caspari and Lee (2004) found evidence that the ratio of older to younger adults (“older” defined as two times the average age of first reproduction) increased significantly in Upper Paleolithic modern humans compared with Australopithecids, early *Homo*, and Neanderthals. In fact, it was only among modern humans that older adults actually outnumbered their younger counterparts. An increased supply of adults may have been important in allowing modern humans to adopt more clearly defined sex roles, with males hunting and females gathering (Kuhn and Stiner 2006). Sex role specialization appears not to have been characteristic of Neanderthals.

*Homo sapiens* were also interacting with other groups more frequently, resulting in raw material and (very likely) informational exchanges (Adler et al. 2006; Feblot-Augustins 1999;

Gamble 1999). The emergence of shell beads sometime between 100,000 and 70,000 ybp suggests that social marking was becoming increasingly important, as would be expected with a rise in intergroup interactions. Furthermore, often these shell beads are found quite distant from their origin, suggesting the existence of expanded trading networks (Vanhaeren et al. 2006). The existence of expanded trade networks is further bolstered by the presence of tools made from “exotic” nonlocal raw materials in the Still Bay and Howiesons Poort tool industries, dated to around 70,000–60,000 ybp (Ambrose 2002, 2010; Henshilwood 2007). Evidence of similarly extensive trade networks is lacking among archaic hominins. Among its myriad impacts, the increasingly sophisticated social world of *H. sapiens* would have had two ramifications relevant to the expansion of working-memory capacity: (1) it would have created a more stable and secure rearing environment for children and (2) it would have put unprecedented stress on social rituals.

#### *Social Complexity and Ontogeny: Allostatic Load and Joint Engagement*

Greater social organization provides a more secure and stable environment within which to raise children. The consistent presence of a sizable older generation among ancestral human groups meant more eyes to supervise and protect children and more hands to procure resources. Often these resources were being procured with increasingly effective technologies that reduced the physical burden on the user (such as lethal projectile hunting weapons). Male specialization in the most dangerous and strenuous activities meant that females could remain closer to camp, expending more energy on child rearing and protection. Additionally, because males and females were specializing in procuring different food resources, scarcity in any one commodity (such as reduced numbers of large game) would not necessarily endanger survival. These factors, in conjunction with intergroup resource exchange networks, resulted in a social, economic, and domestic world of *H. sapiens* that was quite different from that of their archaic contemporaries. Life for *H. sapiens* was not easy, but it was far less precarious than that of any other hominin.

Evidence for this can be found in the fact that Neanderthals and their children endured higher levels of stress and deprivation compared with those experienced by *H. sapiens*. Across most of Europe, Neanderthals were almost exclusively big-game predators (Bocherens et al. 2001, 2005; Marean 2007). Lacking projectile hunting implements, Neanderthals regularly confronted large, dangerous beasts, such as mammoths and rhinos, with spears designed to be thrust in at close range (Churchill 1993; Shea 1997). Unsurprisingly, this tactic produced extensive head, neck, and upper-body trauma (Berger and Trinkaus 1995). The lack of sex role specialization meant that women and youngsters were very likely participating in big-game hunts and sharing in the burdens.

This relative homogeneity in resource procurement also

meant that Neanderthal nutritional needs were more subject to stress when big game became scarce. Analyses of tooth samples show that Neanderthal children endured greater nutritional stress than Cro-Magnon children (Soffer 1994). Moreover, nutritional stress in general seems to have afflicted Neanderthals to a greater degree than Cro-Magnons (Stiner 1991; Stringer and Gamble 1993:166). While evidence of cannibalism (presumably owing to nutritional stress) is present from Neanderthal sites (Defleur et al. 1993, 1999), similar evidence from Cro-Magnon sites is lacking (see Klein and Edgar 2002:198). Neanderthal morality rates were also extremely high—fewer than 10% of Neanderthals lived to over age 35. Among extant hunter-gatherer and tribal agriculturalists, about 50% are over this age (Trinkaus and Thompson 1987). Among the !Kung San of southern Africa, while life expectancy at birth is about only 30 years, nearly 80% of the adult population lives to over age 60 (Blurton Jones 2002:314).

A more secure and stable domestic environment has positive effects on cognitive development. A recent analysis has shown that higher levels of allostatic load during childhood have damaging effects on numerous measures of intellectual performance, including working-memory capacity (Evans and Schamberg 2009). Allostatic load is a composite measure of stress endured during childhood that includes measures taken from blood pressure readings, overnight cortisol and catecholamines levels, and body mass index. Evans and Schamberg (2009) contend that allostatic load represents “an index of chronic stress” representing “the degree of cumulative wear and tear on the body during [the child’s] early lifetime” (6546–6547). The duration and degree of allostatic load incurred during childhood are significant predictors of young adult working-memory capacity. This study confirmed and extended earlier neurocognitive studies by Farah (Farah et al. 2006; Noble, McCandliss, and Farah 2007) showing that an impoverished upbringing detrimentally affected brain systems associated with working memory, cognitive control, and executive functions in kindergarten and first-grade children.

If allostatic stress during ontogeny is detrimental to the development of working memory, then to the extent that the *H. sapiens* social/developmental environment reduced this stress, selection pressure against greater working-memory capacity would have been eased. But a more stable and secure domestic world would also have created positive selection pressure for greater working memory by virtue of greater opportunities for mother-infant joint engagement. Joint engagement refers to instances in which mother and infant share attentional focus together on a third object such as a toy.

The greater number of adults present in *H. sapiens* groups meant that more help was available to the mother, allowing her to devote more time tending to a young infant as opposed to actively gathering or processing resources. By contrast, the high level of skeletal robusticity found in Neanderthal females suggests that mothers (and their children) were highly active, working hard for a living (Lieberman, Devlin, and Pearson



2001; Lieberman and Pearson 2001). Thus, the physical demands on *H. sapiens* mothers were, in all likelihood, not as great as those on Neanderthal mothers, potentially leaving *H. sapiens* mothers more time and energy for child care. To the extent that *H. sapiens* mothers had increased opportunities for joint engagement with their infants, the cognitive development of those infants would have been enhanced.

Infants demonstrate a number of cognitive skills in the context of joint engagement that are either absent or less sophisticated outside of this context (Bigelow, MacLean, and Proctor 2004; Carpenter, Nagell, and Tomasello 1998; Moll, Carpenter, and Tomasello 2007; Ratner, Foley, and Gimpert 2002; Tomasello and Haberl 2003). These skills include word and vocabulary acquisition, organizational abilities, more sophisticated forms of play, and understanding the mental states of others. One possible reason for these cognitive enhancements is that joint engagement heightens cortical activity in infants' brains (Striano et al. 2006).

#### *Building Greater Social Complexity: Social Rituals*

Evidence reviewed earlier indicates that *H. sapiens* social groups were larger and more complex and included more intergroup interactions than did social groups of Neanderthals. But by what mechanism is such a social world constructed? Throughout the animal world, when careful communication is required, ritualized behavior is present. In the current context, "ritual" refers to a stereotyped and generally invariantly sequenced pattern of behavior.

As highly social animals, it is not surprising that primates have an extensive range of social rituals designed to build trust, promote group harmony, and reinforce social relations (Goodall 1986; van Roosmalen and Klein 1988:515). For example, when bonobo, chimpanzee, and spider monkey foraging groups reunite, they engage in a number of rituals of welcoming and social reaffirmation, such as mutual embracing, kissing, group pant-hooting, and grooming. Two male baboons wishing to form a social alliance will engage in mutual scrotum grasping (Smuts and Watanabe 1990). Among chimpanzees, reconciliation between combatants is signaled by bowing and begging gestures (on the part of the loser), followed by kissing and embracing (by the winner; de Waal 1990).

The wealth of social rituals present among our primate cousins indicates that our hominin ancestors were preadapted for using ritualized behavior as a means of social bonding and could call on a rich repertoire of them in their everyday social lives. Thus, faced with the challenge of constructing and managing larger, more complex social groups and communicating carefully and effectively to suspicious out-group members, our ancestors would have naturally turned to a mechanism with a deep history of facilitating social bonding: ritual.

Evidence from traditional societies shows that social rituals are often physically and mentally demanding, requiring great

behavioral discipline and cognitive control. They frequently require one to inhibit reflexive, prepotent responses in order to show commitment to group norms or a willingness to adhere to rules of reciprocity (for a more in-depth discussion, see Rossano 2009). For example, a truce among the Amazonian Yanomamö can be achieved only after warriors show they can resist the taunts, threats, insults, and brandished weapons of their rivals (Chagnon 1968). Rites of initiation common among traditional peoples often require the initiate to endure isolation, deprivation, physical pain, and psychological stress (Catlin 1867; Glucklich 2001; Power 1998: 122–125; Whitehouse 1996). Possibly the most dramatic of these initiations was the famous Mandan Indian Sun Dance ceremony, in which new warriors were suspended from the top beam of a large ceremonial enclosure with ropes attached to skewers embedded in their chests (Catlin 1867). They might remain there for hours or days as dancing and chanting went on below them.

The critical point about these social rituals is that they would have placed great demands on the ability to inhibit prepotent responses while maintaining focus on the need to complete the ritual in order to achieve a highly valued social goal (e.g., acceptance in the group, an alliance between groups, a peace treaty, etc.). Cognitive neuroscience research shows that this ability taxes two parts of the brain integral to working-memory capacity: the dorsolateral prefrontal cortex and the anterior cingulate cortex (Beauregard, Levesque, and Bourgouin 2001; Cunningham et al. 2004; Hester, Murphy, and Garavan 2004; Kelly et al. 2006). Furthermore, increased working-memory capacity allows for greater cognitive resources to be dedicated to conscious inhibitory processes (Kelly et al. 2006). This suggests that in our ancestral past, those with greater working-memory capacity would have had an advantage over others in their capacity to complete successfully demanding social rituals.

## Summary

It is unclear whether the archaeological record supports a progression from icons to indexes to symbols as predicted by Peircian semiotics. The least contentious interpretation is that iconic artifacts (in the form of pigment use) and indexical ones (handaxes with imposed form, composite tools, beads) are roughly contemporaneous (within a time frame around 500,000–100,000 ybp).

Clearly, the move to symbolic thinking arrives later. Its foundations were probably laid in the increased altriciality associated with the expansion in brain size occurring around 500,000 ybp. Given that apes can acquire rudimentary symbol systems, an enhancement of working-memory capacity was probably not essential in giving hominins symbolic potential. Instead, greater working-memory capacity permitted the acquisition of more complex (and more powerful) symbol systems, such as that associated with modern language. The key selective forces behind enhanced working memory were likely

associated with increased social complexity: more demanding social rituals, reductions in allostatic load during childhood, and increased opportunities for mother-infant joint engagement.

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# Imagination, Planning, and Working Memory

## The Emergence of Language

by Eric Reuland

Imagination (leading to planning, culture, “theory of mind”) is a powerful property of the human mind. This article will focus on the relation between imagination, planning, and language. Language is a systematic mapping between arbitrary forms in a medium and interpretations. Its minimal units—words—combine an instruction for realization with an instruction for interpretation. A crucial condition for language to emerge is the ability to access and recursively combine concepts as words by form rather than meaning. I will discuss what such control over lexical access depends on. Using language requires holding forms in working memory while temporarily suppressing their realization and interpretation. A memory system with a buffer able to hold chunks of material of sufficient size is necessary. I will argue that the limiting factor is not so much working memory per se, as understood in the seminal work by Baddeley, but rather the interface/area of overlap between short-term declarative and procedural memory systems as discussed by Ullman. I conclude with a discussion of the relation between the shape of the grammatical system and (limitations on) working-memory processing resources thus conceived.

### Background and Introduction<sup>1</sup>

There is no unique path to survival for a species in a challenging world. So much can be concluded from the relative success of lichens, deciduous trees, ants, shellfish, sharks, rats, doves, and us. Why a species evolved in a certain direction or why a certain evolutionary path seems more successful than another can be assessed only relative to a particular niche—a cluster of challenges posed by the environment in the broadest sense, requiring a particular type of response for survival, such as speed, teeth, massive fat, size, or brainpower.

For many species, their niche is largely determined by the physical properties of their habitat—the limited terrain where their individuals came to be born. Humanity expanded its original niche to include a range of habitats that comprises virtually the whole landmass of our world. At some point—probably just by chance—the genetic variation among the ancestors of one particular branch—ours—included the computational power of their brains, unleashing selective pressure allowing them to go the brainpower route all the way, redefining their niche in terms of the challenges posed by their own kind rather than their physical environment.<sup>2</sup>

The essence of what brainpower got us is *planning*, and planning depends on *imagination* together with the drive for

survival. Put simply, imagination involves the ability to form a mental representation of (some aspect of) the world that deviates from the representation of the world as it is conceived to actually be.<sup>3</sup> Planning is setting out a course of action that is directed at closing the gap between the world as it is conceived to be and such an imagined world (possibly more compatible with one’s desires). Thus, planning is a type of goal-directed behavior that minimally involves a comparison between two mental representations of the world. Planning, therefore, requires a working memory (WM) that is sufficient to hold two such representations.

This dissociates the evolutionary event leading to imagination from the event enabling planning. It is logically possible for some organism to be able to form a mental representation different from the world as it is without being able to effectively use this ability, for instance, if it does not have the resources to carry out a comparison or, alternatively, if it is able to carry out a comparison but only on world repre-

1. In Reuland (2005) I presented some initial thoughts on the issue of imagination. This article presents a further elaboration of these ideas and of material covered in Reuland (2009b).

2. It is important to realize that, to put it bluntly, selection follows mutation and function talk in evolutionary discourse is no more than a post hoc rationalization of what happened.

3. I use “conceived to be” in order to avoid commitment about the extent to which the world can be known. The term *aspect of* reflects that we never have mental representations of the “whole” world. For stylistic reasons I will generally avoid these hedges and just use *world* and *actual world*.

**Eric Reuland** is Professor of Language and Cognition at the Utrecht Institute of Linguistics OTS (Janskerkhof 13, 3512 BL Utrecht, The Netherlands [e.reuland@uu.nl]).

sentations that are too impoverished to be useful. However, there is a difference between the two. Moving from the ability to form mental presentations of the world as it is to the ability to form mental representations of the world as it is not involves a qualitative change, a discontinuity. There cannot be an in-between stage. Moving from a WM that can hold one world representation toward a WM that can hold two world representations is gradual; that is, it makes sense to consider a stage of WM that has more resources than needed for maintaining one representation but not yet enough for two.

So far, we are discussing the formation of mental representations without language. In terms of a Baddeley-type model of WM as discussed by Coolidge and Wynn (2005), this limits the necessary resources to the visuospatial sketch pad. Thus, alternative representations of the world can be formed by various transformations of representations on this sketch pad. Their expressive potential, however, suffers from the limitations of this type of representation: it is restricted to concrete objects and situations. It is language that allows transcending these limitations. In order to see how, let us step back and discuss some basic properties of the language system.

## Issues of Language

Among the less fruitful questions that arise in debates on the evolution of language is the question of how broad our conception of language should be. Is language a unique property of humans? Do animals perhaps have language? If yes, do cats have it, do honeybees have it, or do only we and non-human primates have it? Does it have to be oral, or does the use of signlike fiches qualify? Depending on the answer, other questions concerning the evolution of language may become more and more blurred. Might *Homo erectus* have had language? Did *Homo neanderthalensis* have language? As a linguist I really do not care too much what someone might wish to call language. Broadly, language minimally involves a systematic mapping between forms and interpretations. Forms are realized in a physical medium; interpretations are changes in the state of certain internal subsystems of the mind. What is important is that in humans this form-meaning mapping has particular properties. It is these properties that make human language unique. Enough is known to be sure that our form-meaning mapping is very different from the form-meaning mapping we find in cats or honeybees and also very different from what we find in nonhuman primates. We will come to discuss a number of properties of human language that are undoubtedly distinctive.

What about *H. erectus* or *H. neanderthalensis*? At present, we simply do not know. Can we ever know? The answer relies on how tight our theory of language turns out to be. If human language results from the combination of many independent traits, we will presumably never be able to tell. However, if

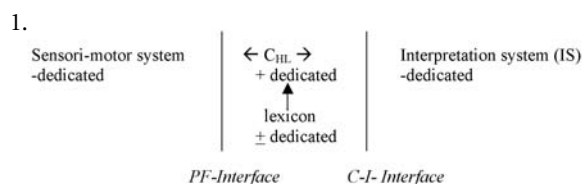
the *prima facie* complexity and richness of natural language reflect only the expressive explosion resulting from the interaction of just a few mechanisms, evidence about mental faculties in domains that allowed evidence to be preserved (from tools to travel) may perhaps tell us something about language. But the conclusiveness of such a demonstration will crucially depend on our understanding of language as we have it.

Human languages typically consist of a vocabulary of lexical elements (words, such as “elephant,” “tiger,” “sloth,” “trout,” “ivy,” “fear,” “run,” and “hunt,” but also elements making up words, such as the plural *-s* in “elephants,” the past-tense element *-ed* in “hunted,” etc.) and principles allowing these to be combined into larger expressions, such as “tigers fear elephants.” Part of our vocabulary (lexicon) is tightly related to our conceptual system, the system that allows us to organize our internal representation of the world.<sup>4</sup>

The concepts of elephant, tiger, sloth, trout, poison ivy, fear, running, and hunting are important to have for any being in something like our niche. Hence, they are not specific to man and not *dedicated* to language.<sup>5</sup> However, certain formal aspects of the lexicon are dedicated to language, such as the fact that word forms are combinable, that they contain properties that are just there to drive to computation, as I will make concrete below; hence, the lexicon as such is  $\pm$  *dedicated*.

A schematic representation of the “language system” is given in 1. Following Chomsky (1995),  $C_{HL}$  stands for the *computational system of human language*.  $C_{HL}$  is, then, a combinatorial system over lexical elements. A combination such as “tigers fear elephants” represents a set of instructions for the system creating sounds (or gestures) and for the system assigning it an interpretation (e.g., one should be able to infer that it is the tigers and not the elephants that are said to hold the fear).

The technical term for the system connecting the sentence to the sound/gesture systems is *phonetic-form interface* (PF interface). The term *conceptual-intentional interface* (CI interface) stands for the system connecting the sentence to the interpretation system. These systems are embedded in what we may broadly call the *human cognitive system* (HCS), the *mind*.



4. This schema does not prejudge the “size” of lexical elements: minimal-size *morphemes*—only stems such as “bear” and affixes such as the plural affix *-s*—or whole constructions in the sense of Jackendoff (2002), as, for instance, “kick the bucket.”

5. In the next section I will discuss semantic properties of lexical items that cannot be readily understood in conceptual terms.

Our capacity for language obviously relies on many processes that are not dedicated to language (expressed as *-dedicated* in 1). Our articulatory system is used for functions varying from eating to respiration. Our auditory system can process sounds irrespective of whether they pertain to language. Our thought system can process a variety of information types that reach us through the different channels provided by our senses.

Syntax ( $C_{HL}$ ) is just the computational system that states what combinations of lexical elements are possible and how parts of the resulting structure are related. Crucial in the study of the evolution of language is the question of how rich the syntactic system is. Current linguistics (as in the *minimalist program*; Chomsky 1995 and subsequent work) seriously explores the idea that the syntactic system as such is very simple and contains only the following principles.

- i. Combine (technically: *Merge*):
  - a) Combine two expressions into a composite expression.
  - b) Specify which of the two determines the further combinatorial properties of the result (the “head”). (Informally, if one combines the adjective “old” and the noun “tiger,” the result—“old tiger”—is a type of tiger, not a type of old. That is, “tiger” is the head of the combination “old tiger.”)
- ii. Agree:
  - a) Check whether two expressions match in features (such as category, person, number, gender).
  - b) Share feature values. (Agree is exemplified in the change of the verb form in “John works” versus “I work.” Languages such as German, Russian, and Latin have agreement systems that are far richer than what we see in English.)

*Merge* goes only little (i.e., in the *ib* clause) beyond an operation that any computational system must necessarily have. *Check* does not go beyond the power that a computational system must have if it contains an identity predicate. Sharing feature values can, in principle, be reduced to merge (overwrite a value with a value that was already there).<sup>6</sup> The next section explores some consequences such a simple system has for our general aim. The syntactic system is coupled with an interpretation system that assigns values to the primitive elements and computes the interpretation of a combination on the basis of these values and the way the primitive elements have been combined.

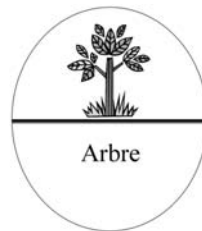
The crucial evolutionary advantage of language is that it allows combinatory operations to apply blindly, irrespective of preconceived meaning. This has an important consequence:

6. If the essence of the linguistic combinatorics does indeed need no more than this, a close relation between the language faculty and mathematics, as suggested by Chomsky (most recently in Chomsky 2008), looks quite plausible indeed. Note that a system ensuing from very simple operations need not be “simple” in expressive power, as just a moment’s reflection on the basic operations of mathematics and its expressive power shows (Kleene 1952 [1971]).

it enables unconstrained creativity; combine and see what the result means later, escaping the limits of the here and now.

The formal rules of language allow us to freely combine concepts, but they also impose interpretations. Combining “square” and “circle” allows us to talk about square circles. We can combine “colorless” and “green” and apply this to ideas, giving “colorless green ideas,” and then go out and find an interpretation, which is not so difficult—just let your imagination flow. Perhaps even more useful applications of these combinatorics are that we can also talk about parallel lines intersecting at infinity, black holes (and why white holes cannot exist), curved spaces, quantum leaps, Schroedinger’s cat, and so forth. What makes this possible?

For many researchers from outside linguistics (e.g., Deacon 1997), language is essentially a symbolic system in the sense of Saussure (1916). That is, it consists of an inventory of concepts coupled with a realization. In Saussure’s conception, a sign is an arbitrary conventional pairing between a form in some medium—a *signifiant*—and a meaning/concept—a *signifié*—as in the venerable example in 2.



However, the conception of language as a symbolic system is by far not enough to give us the power language has. There are many abstract concepts that cannot be represented pictorially. But the core feature of language that unleashes creativity is—perhaps paradoxically for some—its *desymbolization* (see also “The Effect of Adding Recursion to a System without It”): combine forms irrespective of their meanings, and then interpret the result.

It is the desymbolization of language that allows us to ignore common sense, play with expectations, express the inconceivable, escape from the here and now, and create poetry. It is the possibility to create models of unlikely, hard-to-conceive, and completely impossible states of affairs that enables us to escape the limitations of the visuospatial sketch pad. Thus, desymbolization feeds into imagination and gives rise to the richness and diversity of human culture.

## Issues in the Evolution toward Language

Currently, one of the important debates in cognitive science is about the question of what is special about language (see Fitch, Hauser, and Chomsky 2005; Hauser, Chomsky, and

Fitch 2002; Jackendoff and Pinker 2005; Pinker and Jackendoff 2005): what sets our linguistic abilities apart from what we see in even the most closely related nonhuman primates? As we saw in “Issues of Language,” the computational system of human language enables a mapping between forms and interpretations. The mapping is based on an inventory of lexical elements representing elementary form-meaning pairs and a combinatorial system. The lexical elements allow access to a conceptual system. Further requirements for language include memory systems (Baddeley 2000, 2001; Coolidge and Wynn 2005, 2006; Ullman 2004). Using language requires planning—planning what to say and how to say it—to go from intention to articulation (Levelt 1989).

What do we find in nonhuman primates? They have an expression system that is not incompatible with language. They have a conceptual system, memory systems, and at least rudimentary planning. But even though they have all these in some form, they do not have language.

Hauser, Chomsky, and Fitch (2002) and Fitch, Hauser, and Chomsky (2005) explore the idea that the reason why this is so resides in the combinatorial system: humans have *recursion*; nonhumans do not. For Chomsky (2008), recursion requires no more than merge in the sense introduced above. The possibility to combine linguistic objects in such a way that object 1 + object 2 yields a *composite object of the same type*, that is, an object that is in turn amenable to concatenation. This gives composite linguistic objects in unlimited numbers.

Pinker and Jackendoff (2005; Jackendoff and Pinker 2005) argue that there is no reason to single out recursion and the human *syntactic* combinatorial system. This immediately bears on a question that plays a key role in current debates on the emergence of language. What type of evolutionary event do we have to look for? Take a protohuman in the “final stage” before language: what is the emergence of language the result of? *Gradual changes* in what was already there? Changes that are adaptive, continuous, quantitative, that develop as responses to selective pressure? Or does it involve *discontinuities*? Newly emerged traits that make a qualitative difference? Traits that initially emerge by a random event (such as mutation or incorporation of viral material) and have not been selected for? (Selection applies after the event but does not influence the event itself.)

There can be no evolutionary pressure on a trait unless that trait is already there as a “target.” At each evolutionary turning point, there must have been an evolutionary event that cannot be understood in adaptive terms alone. Hence, if we want to understand the events leading to language, we must focus on those changes that (i) are constitutive of language and that (ii) cannot be gradual, and then we need to look for concomitant genetic changes.

Comparing the cognitive faculties underlying language and their functional homologues in nonhumans, we see an important asymmetry between recursion and other possible factors. There are many factors that can change gradually, for

instance, WM,<sup>7</sup> accuracy of articulation, suppression of breathing, vocal range, speed in lexical access, and so forth. There cannot be a gradual change in *recursivity*: recursivity is a yes-no property. Hence, the transition from a system without recursion to a system that has it must be discontinuous. If we want to understand the emergence of language, it is crucial to identify those steps that are necessarily discontinuous. Hence, those are the steps my discussion will focus on.

## The Effect of Adding Recursion to a System without It

Elsewhere (Reuland 2009b) I discuss the effects of adding embedded recursion to a system without it, given that the resulting structures have to be squeezed through a linear channel. I will briefly recapitulate that discussion here. Let us start out with a system just having Saussurean signs that can be sequentially realized. As we saw in 2, a Saussurean sign is a meaning paired with arbitrary form—arbitrary because, in general, a name does not tell us what it means. This conception is represented in 3.

3. *Sign*:  $\langle f, i \rangle$ , where  $f$  is a form in a medium (sound, gesture) and  $i$  its interpretation as a concept.

Of course, *arbitrariness* by itself is already a yes-no property, a property that reflects a *discontinuity* in evolutionary terms. But having signs does not entail having recursion. Recursion requires concatenation, combining two objects into a composite object that is in turn available for concatenation (Chomsky 2008). Linguistic signs, therefore, must be triples of the general form in 4 rather than pairs, as in 3.

4.  $\langle f, g, i \rangle$ , with  $f$  and  $i$  as above and  $g$  a formal instruction driving the computation, minimally allowing combinability.

The addition of  $g$  leads us beyond the Saussurean sign. It is a minimal change, but it is *qualitative* in nature. Adding this property to the sign opens the door for purely grammatical “machinery.” Such a system has recursion but of a simple type (unless restrictions are added): it is a finite-state grammar (Chomsky 1957), or, to use a different term, it has *tail recursion*—material is added only at the periphery.

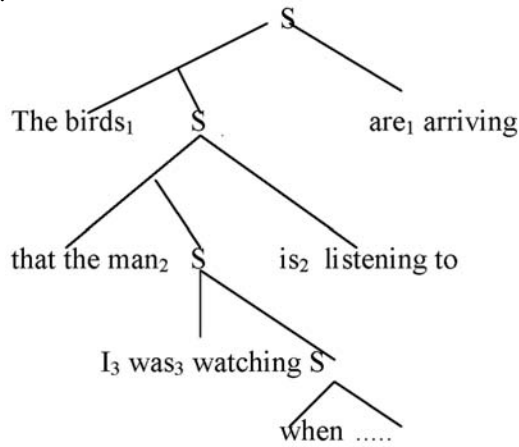
Language as we know it involves more than tail recursion. As is easily seen, nested dependencies as in 5 abound, where the symbol  $S$  stands for a sentential structure. Sentences in natural language can contain sentences. Noun phrases can contain sentences that in turn contain noun phrases. Properties of a particular noun phrase determine properties of the following verb phrase because finite verbs agree with their subjects. Nesting structures that arise because of the fact that *noun phrases* such as “the birds” can be modified by a *relative clause* are illustrated in 5. This relative clause can in turn

7. Much of my discussion of working memory has been inspired by the intriguing work of Coolidge and Wynn (2005, 2006; Wynn and Coolidge 2010, in this issue). Their work shows that progress in understanding depends on an inspiring vision.



contain an expression that is modified by a relative clause, and so forth.

5.



A dependency between “the birds” and “are” is shown in 5, separated by a dependency between “the man” and “is,” in turn separated by the dependency between “I” and “was.” Note that at many points there can be further expansion. Adjectives can be added to “man” and “birds” and adverbial modifiers to “arriving,” “listening,” and “watching,” both as single adverbs and in the form of full clauses, such as the “when” clause indicated. When the structure is put on paper, it may seem that little changes in principle by a “transition” to a system allowing nested dependencies. But it is easy to see that appearances are deceptive.

Language is realized along one spatiotemporal dimension. Hence, an instruction such as “realize the sequence (1) ‘the birds . . . are arriving’ and put in the middle another sequence (2) ‘that the man . . . is listening to,’ etc.,” cannot be carried out in the spoken language channel. Instead, while carrying out one instruction, it must be temporarily halted and the next instruction started, and the system returns to the initial instruction only after completing the second one, and so on. So, in the case of nested dependencies as in 5, the procedure starts the process of realizing sequence 1 but temporarily halts this instruction after realizing the initial part “the birds”; retains in memory that at some point the final part “are arriving” has to follow and not “is arriving”; starts realizing the next sequence with its initial part “that the man,” halts, and so on; and after realizing the last *initial part* and the first final part, returns to the next instruction to finalize a sequence, carries it out, returns to the next instruction waiting in line, and so on, until the store of instructions is empty. Thus, given the properties of the medium, embedded recursion—necessary for linguistic dependencies—requires that material stays internally represented, not only before but also after it is realized. The system must keep track of what it has done in order to carry out what has to be done. Hence, the process requires sufficient WM to keep the necessary information in store.

This has a further consequence. The elements the system

operates on can no longer have the form in 4, repeated in 6a; rather, they must have the form in 6b.

- 6. a)  $\langle f, g, i \rangle$ , with  $f$  a representation,  $i$  a concept, and  $g$  driving the computation.
- b)  $\langle c_f, g, c_i \rangle$ , where  $c_f$  and  $c_i$  are “formal” mental encodings of relations with the language’s external systems of realization and interpretation.

Thus, what must be stored is not the sign but the instruction to create a sign. What the combinatorial system operates on are therefore not the signs but the instructions to form signs. This is in fact a further qualitative change. It leads to the *desymbolization* referred to in “Issues of Language,” turning language into a formal system.

Because we are dealing with instructions to form signs and the system has to be able to hold up realization anyway, this opens the door to more abstract computations: instructions for interpretation that are never realized as “independent” lexical elements, *functional* elements that contribute abstract instructions for interpretation.

### Structure, Lexical Items, Expressions, and Interpretation

In order to see what is involved, let us consider the following inventory of arbitrary minimal form-meaning combinations.

- 7. Objects: tree, deer, elephant, ant, man, spear, hut, . . .
- Activities: hunt, see, run, . . .
- Properties: green, gray, square, . . .

These are typical instantiations of the linguistic categories *noun*, *verb*, and *adjective*, respectively. Note that all these expressions refer to concrete objects, properties, and events. But in addition to a verb “hunt,” we can also form a noun “hunt.” This noun can in turn serve as an argument of predicate, as in “The hunt was successful.” Like hunting events, fishing events, warring events, and so forth can be successful (or not). Also, the property of being successful can be turned into a nominal and serve as an argument, as in “The success amazed the enemy.” Human language abounds in expressions with an “abstract” interpretation—such as “beauty,” “wish,” and “attractive”—all dependent on an operation of abstraction, yielding an unbounded semantic space orthogonal to the syntactic space created by combinability but crucially dependent on it.

Does the ability to create abstract nouns involve a discontinuity? This is not evident. It is very possible that the only formal discontinuity in human evolution along this dimension involves the ability to apply abstraction to internal linguistic representations. If so, there need not be a difference in principle between generalizing along a dimension of “elephanthood,” “hunting,” or “success.” It is ultimately an empirical matter, however, whether all types of abstraction are on a par.

Note that abstract concepts typically involve mental states,

the internal versus the external world. This may well be the heart of the matter: being able to create representations of the internal state of the mind and handle them just like representations of the external world, applying abstraction not just to objects in the external world but also to linguistic representations.

Expressions for internal states (“want,” “know”) coupled with combinability provide a crucial ingredient for a theory of mind: “I want,” “John knows,” “John knows that I want,” “I want that John knows that I want,” and so on. Note again that there is a distinction between availability in principle and the ability to use. Even if the tools are available for creating complex propositional structures, there is no guarantee that WM systems will be able to hold them.<sup>8</sup>

As noted in “Issues of Language,” it is a crucial property of human language that combinability goes hand in hand with instructions for assigning interpretations, a point underrepresented in Hauser, Chomsky, and Fitch’s (2002) discussion (see also Fitch, Hauser, and Chomsky 2005). Immediately associated with each combinatorial step is an interpretive rule specifying how the interpretation of the composite expression is derived from the interpretation of its parts.

Such interpretation rules operate on expressions in terms of their structure. In deriving the interpretation of “mice chase cats,” combining “chase” and “cats” is associated with a different interpretation rule than combining “chase cats” with “mice” (even if these rules may in fact be very similar). In turn, this rule must be different from the rule applied in deriving the interpretation of “bald king” from the interpretations of “bald” and “king.” (That a precise formulation of this rule is not trivial can be seen by comparing the contribution of the adjective “big” in “big elephant” and “big butterfly,” where the adjective receives a relative interpretation: “big for an *x*,” filling in “elephant,” “butterfly,” etc.; see Higginbotham 1985). For current purposes, this discussion suffices.

All this does not yet give us language as we know it. Consider a sentence as in 8.

8. The Vandals *will* depend on the destruction of Rome for their place in history.

The expression “the Vandals” can be valued by a mental entity corresponding to a particular tribe and the expression “Rome” by a mental entity corresponding to a particular city. The nouns “destruction,” “place,” and “history” reflect abstract concepts that can receive specific values in particular situations. The same holds for the verb “depend.” “In” and “for” express relations between such values. However, it requires

8. Note that combinability and expressions for mental states are prerequisites for a language of politeness as discussed by Ambrose (2010, in this issue). But the force of selection and the order of development cannot be the other way round. Having language creates many advantages, but there is no single “function” of language, just as there is no single “function” of the hand.

little reflection to see that no concept is associated with the prepositions “on” and “of” in 8. One would be hard-pressed to say what they *mean* here. They do contribute to the interpretation, however. “On” formally marks the relation between the verb “depend” and its complement, “the destruction of Rome,” and “of” marks the relation between the noun “destruction” and its complement, “Rome.”

Thus, the expressions “on” and “of” in 8 have the following property: they operate on pairs of expressions yielding instructions for how to interpret that particular combination. So, natural language has *expressions operating on expressions*. This is in fact another yes-no property. Does it require an independent leap? Prima facie one might say yes. But reflection suggests a different option. A crucial property of language expressions is that they have a dual status. On the one hand, they have an interpretation. On the other, when realized in sound or gesture, they are truly physical events in the external world. As such they can be perceived and thus become part of the mental world again. Also before realization, they have a concrete status, as a series of motor instructions set up and planned to be executed. So if “on” and “of” are valued as relations between expressions, by the same token they are also valued as relations between the mental objects corresponding to these expressions. But because all expressions are valued as mental objects or relations between them, this is not a difference in principle.

The crucial step, therefore, may well have been that expressions are valued by mental objects. By this token, anything that qualifies as a mental object—including expressions themselves—may enter into the interpretation instructions for linguistic expressions, which yields recursion in the meaning dimension, not as a mechanism parallel to syntactic recursion but as one orthogonal to it, recursively defining types of meanings.

What about determiners such as “the”? Again, there is no concept they express. Rather, they link an expression to the discourse. A felicitous use of “the” requires that there is a uniquely identifiable element in the discourse that serves as a value for the expression that is headed by “the.” To use a well-known example, the sentence “The present king of France is bald” is infelicitous because there is no individual in the discourse that values the expression “present king of France.”

With determiners we enter the domain of quantification. For a simple illustration of what is involved, consider the following contrast:

9. a) John ran.  
b) Every boy ran.

For 9a to be evaluated, we need just to consider John and determine whether he has/had the property of running. In the case of 9b, we cannot do it that way. “Every boy” does not denote an individual as “John” does. For 9b to be evaluated, we have to consider two sets—namely, the set of boys and the set of runners—construe the intersection of the two,

and determine whether there are boys that are not runners. Thus, for every  $x$ ,  $x$  a boy, we have to determine whether  $x$  is a runner. Carrying out this computation requires using variables (or a close equivalent).

Variables are not lexical items. The best approximation we can get to what variables are—if we take Saussurean signs as our starting point—is that they are temporary stand-ins for individuals. The existence of variables and quantificational structures in general may well involve an independent discontinuity.

Whereas the elements discussed so far play a single role in the computation, in other cases expressions play a dual role, as in 10.

10. Which city did the Vandals destroy?

“Which city” has the role of the object of “destroy,” and it also marks the sentence as a question. The dual use of expressions is a pervasive property of natural language. A way of expressing it (standard in certain versions of modern syntactic theory) is by a copying operation, as in 11.

11. Which city did the Vandals destroy (which city)?

The canonical term for the relation between the fronted copy and the one in parentheses is *movement*; a more general term is *dislocation*. The lower copy is put in parentheses to indicate that it is not sent off to the realization system.<sup>9</sup> For our present purposes, it is important that movement is one of the operations natural language has to mark dependencies.<sup>10</sup> There are other operations expressing dependencies; however, they differ in some of their properties. As we will see in the next section, these differences provide a window into the role of WM in natural language.

## Computing Interpretive Dependencies

Dealing with dependencies requires a WM that can store information for subsequent retrieval. This holds regardless of whether these dependencies are there because of nesting, as in 5, or because of movement. Our further discussion will focus on two properties that bear on the role and structure of WM: (i) anaphoric relations and (ii) locality restrictions on movement.

### Anaphoric Relations

Natural language allows different expressions to receive identical values in some actual or virtual world. For instance, in our world, English “morning star” and “evening star” both have the planet Venus as their value. That is, both *refer* to Venus. Such expressions are *coreferential*. Coreference may

9. The claim that “which city” performs a dual role is independent of one’s pet theory of natural language. Any account, irrespective of theoretical view, will have to express this dual role.

10. Movement also plays a role in the interpretation of certain *anaphors*, such as English “himself” (Reuland 2008).

reflect an empirical fact, as in the Venus case, but it also reflects the speaker’s intentions. A pronominal such as “he” can be used to refer to any object that is linguistically classified as masculine and singular, as in “Ben’s mother thought he was a hero.” Here, “he” may refer to Ben but also to some other masculine individual. Crucially, coreference is a matter of the relation between language and the world representation; it is not *encoded* in the language.

There is another way, however, to relate the interpretation of two elements. “No one” in “No one believes he is guilty” does not refer to an individual; hence, a fortiori, “he” cannot refer to that individual. However, “he” does depend on “no one” in one salient interpretation. In this case the dependency is linguistically encoded. This is called *binding*.

The difference between binding and coreference is well illustrated by the contrasts between the following texts (see Heim 1982). Coreference is possible across sentences, as in 12*a*, where “John” and “he” can be independently used to refer to the same individual. But “everyone” and “no one” in 12*b* are not referential; hence, an interpretive dependency between “he” and these expressions cannot be established through coreference. Binding, the other option, is not available cross-sententially. Hence, the sequel in 12*b* is not felicitous. That there is nothing wrong with “he” being *bound* by a quantificational expression is shown by 13.

12. *a*) John has a gun. Will *he* attack?

*b*) Everyone/No one has a gun. \*Will *he* attack?

13. *a*) John was convinced that *he* would be welcome.

*b*) Everyone/No one was convinced that *he* would be welcome.

Binding is thus an interpretive dependency that is encoded by a process of the *grammar*:

14. An expression—*he*—is interpreted in terms of another expression (*John, everyone, no one*).

To summarize,

15. There are two qualitatively different ways in which a pronominal can be interpreted: (i) by direct assignment of a value and (ii) by being linked to another expression and deriving its interpretation from the interpretation of the latter expression by a linguistic computation.

The latter route crucially depends on desymbolization of the pronominal, and it is the latter route of interpretation, not the “direct” referential route, that underlies quantification in natural language. The step from coreference to binding involves a discontinuity, but it is presumably the same discontinuity discussed in “Structure, Lexical Items, Expressions, and Interpretation,” namely, allowing expressions to be valued in terms of other expressions.

Binding relations are subject to further constraints. *Binding theory* is the component of the system that is concerned with the way in which anaphors (elements such as English *himself*, Dutch *zich* and *zichzelf*, and their cognates in other languages) and pronominals are related to their antecedents (Chomsky

1981; Reinhart and Reuland 1993, Reuland 2001, 2008). For reasons of space, I will not discuss them here and refer to the references cited for discussion and to Reuland (2009*b*) for some remarks in an evolutionary context. Rather, I will contrast the binding of pronominals with movement dependencies.

### Locality

Movement dependencies are subject to restrictions. Item 16 lists a couple of possible and impossible questions. Because in English, question words have an initial *wh*, the usual term for the process of question formation is *wh movement*. Below, moved elements are marked by italics. The position they relate to is also given in italics and put within parentheses. The latter position is not pronounced, but for purposes of interpretation it is there. Some restrictions on *wh* movement are illustrated by the ill-formedness (indicated by the asterisk) of 16*d* and 16*f*. These sentences show the existence of so-called *locality restrictions* on movement.

16. a) John asked whether Bill saw the hill.  
 b) John asked *what* Bill saw (*what*).  
 c) John asked *who* saw the hill.  
 d) \**What* did John ask *who* saw (*what*).  
 e) *What* did John think Mary told Bill she heard Suzy say (*what*)?  
 f) \**What* did John think Mary would be unhappy after she ruined (*what*)?

16*d* is ill-formed because of “what” crossing another question word, “who.” The ill-formedness of 16*f* instantiates another restriction, which is a solid cross-linguistic generalization: *No element can move out of an adverbial clause*. Adverbial clauses are absolute “islands” for movement.

Note that there is nothing wrong with the meaning of ill-formed sentences such as 16*f*. Consider 17.

17. a) John thought Mary would be unhappy after she ruined his apartment.  
 b) What it is that John thought Mary would be so unhappy about after she ruined it?

The question in 17*b* modeled on 17*a* represents the intended interpretation of 16*f* quite well. So, the issue is not that some meaning cannot be expressed; the issue is that a particular operation that is usually available to express questions is not available under certain conditions. The question then is why.

Motivating a particular theory of locality would lead us far beyond the scope of this article. Most current conceptions of grammar agree that the grammatical system must operate in such a way that overload of processing resources is prevented. This requires cutting up the sentence in chunks in such a way that the number of chunks in the work space is limited.<sup>11</sup> Accordingly, the ill-formedness of 16*d* and 16*f* could well be

11. To my mind the most promising perspective is presented by the theory of phases proposed by Chomsky (2001, 2008).

due to the fact that they are in different chunks that cannot be stored in the work space together.

Many details aside, there is one puzzling fact that motivates a careful consideration of the nature of the grammatical work space.

18. The relation between a pronominal and its binder is not sensitive to locality.

That is, the dependency exemplified in 19 is entirely fine:

19. *Every boy* thought that Mary would be unhappy after she ruined *his* apartment.

Here, “his” depends for its interpretation on “every boy” in the matrix clause. Just as in 16*f*, the dependent element “his” is in an adverbial clause. But in this case there is no problem. The question then is how this is compatible with a work space perspective on dependencies, because “every boy” and “his” must be in the same work space in order for the dependency to be computed. Is it conceivable, then, that there are two types of work spaces? Let us therefore consider two issues concerning WM.

## Issues Concerning Working Memory

### *Baddeley's Working-Memory Model: A Starting Point*

An influential model of WM has been developed by Alan Baddeley (summarized in Baddeley 2007). This model of WM also underlies the work on the relation between the evolution of WM and the evolution of language in Coolidge and Wynn's (2005, 2006) seminal work. WM in this model is a buffer in which information is stored for further operations and that may be consciously accessed. To use a lucid example, the cover of Baddeley's (2007) book shows a self-portrait by Gauguin, which was—as the text goes—“presumably painted using a mirror, and hence from memory: working memory.” From a more linguistic perspective, there is an influential paradigm of studying the representation of causal relations that uses implicit versus explicit indicators of causality (see Sanders and Noordman 2000). Compare, for instance the minidis-courses in 20 and 21.

20. a) Because all hell was breaking loose, John started to make preparations for his escape.  
 b) All hell was breaking loose. John started to make preparations for his escape.  
 21. a) Because the lights stayed on, John must have been at home all night.  
 b) The lights stayed on. John must have been at home all night.

The nature of the relations differs in the two cases. In 20, the relation is one of simple causation. In 21, the relation is one of justification. However, in order to account for the fact that we can assess this difference, the essence of the information must stay alive as long as it takes to process the whole text. Thus, rather complex chunks of information must stay ac-

cessible in the course of processing and interpreting texts. For current purposes, the key phrase here is “conscious access” and also a relatively substantial and flexible free space.

It is unlikely that the types of cost incurred in computing dependencies as in 16*d* and 16*f* comes close to filling the total “free memory space,” given that the space must be sufficient to contain relatively large text chunks or sequences of instructions for painting a self-portrait. This indicates that capacity is task sensitive, suggesting that different subsystems are involved. Research on child language acquisition and agrammatic aphasia also indicates that tasks involving questions and certain other dependencies come closer to taxing a memory system to its limits (e.g., Grodzinsky and Reinhart 1993; for an overview, see Avrutin 2001).

Size and span of WM are typically measured by tasks involving the memorization of strings of digits, interference of the other tasks with digit recall, and so forth. One of the standard measures for WM span is formed by nonword repetition tasks. The question then is how relevant WM is, as measured along these lines, for linguistic tasks. Interestingly, as reported by Thal et al. (2005), it is possible to achieve normal language skills with poor nonword repetition abilities and to develop poor language skills when nonword repetition abilities are good (Bishop, North, and Donlan 1996; Botting and Conti-Ramsden 2001).

All this suggests that more is needed than a Baddeley-style WM to understand the relation between memory systems and language. This will be taken up in the next subsection.

#### *Ullman's Declarative-Procedural Model*

Ullman (2004) discusses the contrast between declarative memory and procedural memory. The former contains conceptual/propositional information and is—relatively—consciously accessible. The latter is a repository of automatic skills largely related to the motor system. It is implicit and encapsulated (not consciously accessible). Roughly, declarative memory involves lateral/inferior temporal lobe structures and medial temporal lobe structures, whereas procedural memory involves frontal and basal ganglia structures in the dominant hemisphere.

Ullman proposes that the contrast between these two systems is also reflected in language. The lexicon, especially the content words, is stored in the declarative system; the grammar, whatever is rule-based in the language, is stored in the procedural system. Even from functional considerations alone, it follows that the two systems cannot be completely separated. According to Ullman, the lexical/declarative memory system and the grammatical/procedural system can be hypothesized to interact. The procedural system should be able to build complex structures by selecting lexical items from declarative memory and maintaining and structuring those items together in WM. The same or similar types of knowledge can, in at least some cases, be acquired by both systems. The two systems must also be able to compete be-

cause a representation of, for instance, an irregular past-tense form—such as “swam”—stored in the declarative system, must be able to block access to the “regular” form \**swimmed*, which involves the procedural system. So the systems must be able to “talk” to each other. Producing and understanding utterances in a language involves both the grammar and the lexicon, so there must be a buffer where lexical items, or “pointers” to lexical items, can be temporarily stored and used as the input for grammatical processes.

As Ullman points out, there are indeed structures with mixed roles. Certain brain structures that underlie procedural memory also perform context-dependent selection and maintenance (in WM) of knowledge stored in declarative memory. Whether these structures are considered to be parts of the procedural system that play a role in declarative memory or vice versa is only a terminological issue in his view. He suggests that these are most reasonably brain structures that play particular roles in both systems.<sup>12</sup> It follows, then, that crucial for the grammar part of language processing and production is not so much WM at large but rather the interface between procedural and declarative memory systems.

In “Issues in the Evolution toward Language,” we saw that the essential evolutionary step from a functional perspective was adding recursion to a systems of signs, implemented as combinability of signs, and what this further entailed given the properties of the channel. Rather speculatively, we can now formulate the following hypothesis:

22. A crucial step in the neurocognitive systems facilitating language involved enhancing the interface between declarative and procedural memory systems.

A possible further hypothesis is, then, that it is this interface rather than WM as a whole that is a bottleneck in the language system. If so, we will expect that locality and the necessity for chunkwise (phase-based) processing is limited to only those dependencies that are syntactically encoded and hence make crucial use of this limited buffer. If correct, this immediately explains our puzzle: why is dislocation sensitive to locality but not pronominal binding?

Consider first *wh* movement. Crucially, a *wh* element in fronted position carries on its sleeve that a dependency follows: on the one hand *wh* must be semantically integrated in the initial position as expressing that we are dealing with a question; on the other hand, it must relate to the verb (*V*) to express what the question is about. It cannot be integrated with the verb in the position in which it is encountered. So, the general configuration shows a dependency between two positions of the *wh* element: *wh* .... *V* (*wh*). This holds for both interpretation and production.

A *wh* element in the incoming utterance indicates that at some later point the utterance must contain a position the

12. Superior aspects of the temporal lobe may play some function in the procedural system, perhaps as a storage repository of procedural knowledge, and the same or nearby areas of ventrolateral prefrontal cortex play related roles in declarative and procedural memory.

*wh* has to provide a value for. Whether it is compatible with such an upcoming position will be determined by properties of the local environment. To the extent to which grammar is part of the procedural system, this entails that the full item be kept in what one may call the *declarative-procedural interface* (DPI).

In production, a *wh* element in the utterance as it is being realized should also be retained in the DPI, because it has to be guaranteed that subsequently the utterance contains a position it can provide a value for. Moreover, it should match with properties of the verb (e.g., if it has the form “whom” in English, it cannot be a subject). Therefore, it must stay available for matching.

Thus, movement is always visible on the first/leftmost copy. This entails that a formal dependency requirement must be carried along during interpretation or production, if only in the form of the requirement of valuing the lower/lowest position or not pronouncing the lower/lowest copy. It must be available for formal integration, which requires it to stay in the DPI.

The case of binding is different because the potential binder is self-sufficient. Although “every boy” in 23*a* may bind a pronominal, nothing requires it to do so, nor does a pronominal need to follow, as illustrated in 23*b*, which is fine. Compare this with the ill-formedness of 23*c*, which does not contain a position the *wh* element can be related to.

23. a) *Every boy* thought that Mary would be unhappy after she ruined *his* apartment.  
 b) *Every boy* left.  
 c) \**What* did John read that book.

This means that a potential binder qua binder does not depend on the procedural system for its integration. In interpretation, integration with its bindee, if there is one, can take place in declarative memory after it has been sent off from DPI. In production, its formal properties need not be retained in DPI after it has been realized.

I offer the hypothesis that indeed, using a term from Ullman in a slightly different vein, there is a *seesaw effect* in the access of declarative and procedural memory in the production and interpretation of utterances that is mediated by the DPI. This DPI, then, is the bottleneck. It is the limitations on DPI that require grammatical processes to apply to chunk-type packages. Given what is known about Broca’s area, it is a reasonable hypothesis that systems in this region play an important role in the DPI. Pursuing Coolidge and Wynn’s (2005, 2006) proposal that some evolutionary event in the time frame between 150,000 and 30,000 years BP led to an enhanced WM, one should investigate whether this event could have involved the DPI.

## Conclusion

The evolutionary event leading to language need have been no more than an event enabling manipulating instructions

rather than full signs and establishing a link between the procedural and declarative memory systems. Restrictions on processing capacity in DPI favor making the computations as efficient as possible, specifically the use of formal markers to encode relations that will be interpreted in the declarative system. But still, a minimal processing capacity would have been needed to get the process going at all. This leads to the thesis in 24.

24. A qualitative change may depend for its effectiveness on a quantitative change.

Consequently, it is important to strictly distinguish between the following two stages in the evolution of humanity.

25. i) The event that gave rise to the faculty of language as we know it.  
 ii) The subsequent evolution of humans and the emergence of language.

It is logically possible that the genetic event responsible for the discontinuity required for embedded recursion, that is, the event enabling the emergence of combinability—which we might equate with the option to hold a lexical item in DPI postponing its realization and interpretation—occurred at a stage that DPI was not yet able to hold proposition-size chunks. This could have been followed by a gradual increase in DPI, potentially driven by language-independent factors. Consequently, there may have been a time lag between the emergence of the language faculty, that is, the moment that language became *possible* and the time the language faculty became fully *usable*. This provides an interesting perspective on the monogenesis of language. I will indicate some logical possibilities as issues to explore.

Clearly, the event allowing embedded recursion is constitutive of language and must be shared by all humans. And it has yet to be established what part of our genome could have been involved.<sup>13</sup> Similarly, an event *allowing* the expansion of WM and DPI must also be shared. However, what cannot be excluded is that the actual gradual expansion of WM and specifically DPI was driven by an evolutionary process within a sufficiently similar niche, as determined by a common evolutionary path but completed in different populations after migration had set in, for instance, after the exodus from Africa (see Oppenheimer 2004). If so, it is possible for language as we know it to have started in different places. But note that this is only a logical possibility. It is equally possible that a substantial enough DPI was already in place at the moment the conditions for recursion came to be met. If so, language may well have arisen without much time lag, and monogenesis is reasonable. Interestingly, only the first option is compatible with speculations about protolanguage as an impoverished

13. See Reuland (2009*a*) for a suggestion to consider the last mutation in the FOXP2 gene as discussed by Enard et al. (2002) and Vargha-Khadem et al. (1995, 1998) as a possible source of the control necessary for the suppression of realization in planning the production of utterances.

system and various restricted language systems as providing windows into the genesis of language (Arbib 2004; Botha 2006; Jackendoff 1999, 2002).

Presumably, all functional elements derive from full lexical items by *grammaticalization*, a process by which lexical elements become semantically bleached and in the end lose their lexical semantics entirely. From the current perspective, the pervasive role of grammaticalization processes in natural language has a deeper cause than just “wear and tear” but derives from computational optimization kept in check by the fact that not every lexical element can become grammaticalized, assuming some content has to be expressed in the end.

What does this tell us about the first stage of natural language after it emerged? Grammaticalization may have been an important factor right from the start, and it should not have taken much more than a generation after the event for functional elements to develop. What if processing capacity of early humans was still limited as compared with ours? If so, the need to opt for content may have affected the use of functional elements. Therefore, here, too, it is of the utmost importance to separate claims about a system from claims about its use.

Let me end with a note on language and planning that is perhaps even more speculative than what I wrote so far. Using language depends on planning, planning on the level of what one wants to achieve by saying something, planning what to say, and planning on the level of instructions to the motor system of how to say what one wants to say. Much of this planning is conscious and hence takes place in the declarative part of WM. But it is an interesting observation that it is extremely difficult to handle concepts without a concomitant form—the tip-of-the-tongue phenomenon—not just for the purpose of speaking but to handle them in general. But what is a form? As discussed, a form is a package of instructions to the motor system (either the articulatory system or the gestural system). It seems then that we have to plan in terms of motor sequences. This brings us back to a suggestion of Hauser, Chomsky, and Fitch (2002) that the faculty of language borrowed features of the navigation system. In “Background and Introduction,” I suggested that imagination is limited as long as it is confined to the concreteness imposed by the visuospatial sketch pad. Suppose, then, that our imagination is indeed limited to what can be achieved by the handling of “concrete” objects. It is the ability to connect (instructions for) motor sequences and concepts and the ability to combine such sequences that allowed us to escape the effects of this limitation.

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# Compound-Adhesive Manufacture as a Behavioral Proxy for Complex Cognition in the Middle Stone Age

by Lyn Wadley

Compound adhesives were made in southern Africa at least 70,000 years ago, where they were used to attach similarly shaped stone segments to hafts. Mental rotation, a capacity implying advanced working-memory capacity, was required to place the segments in various positions to create novel weapons and tools. The compound glues used to fix the segments to shafts are made from disparate ingredients, using an irreversible process. The steps required for compound-adhesive manufacture demonstrate multitasking and the use of abstraction and recursion. As is the case in recursive language, the artisan needed to hold in mind what was previously done in order to carry out what was still needed. Cognitive fluidity enabled people to do and think several things at the same time, for example, mix glue from disparate ingredients, mentally rotate segments, talk, and maintain fire temperature. Thus, there is a case for attributing advanced mental abilities to people who lived 70,000 years ago in Africa without necessarily invoking symbolic behavior.

## Introduction

What is complex cognition? The type of cognition attributed to people who think like us includes among its attributes “cognitive fluidity” (Mithen 1996), the ability to employ innovative thoughts, a capacity for novel and sustained multilevel operations (Amati and Shallice 2007), abstract thought (Barnard 2010, in this issue), and the use of recursion and concepts of past and future (Haidle 2010; Reuland 2010, both in this issue). Executive functions of the brain, which depend on frontal lobe-linked abilities, enable many of these attributes of complex cognition, and additionally, executive functions facilitate goal-directed actions, anticipation of problems, analogical reasoning, and planning over long distances or time (Coolidge and Wynn 2001, 2005; Wynn and Coolidge 2003). Examples of the type of innovative technologies implied by executive functions include alloying metals and the production of kiln-fired ceramics (Coolidge and Wynn 2006; Wynn and Coolidge 2007*a*, 2007*b*). Both are based on the ability to bring together disparate raw materials, often from distant separate sources, and to transform them, sometimes irreversibly. Combinability, also found in recursive language (Reuland 2010), occurs in the transformation of two or more metals into one.

**Lyn Wadley** is Honorary Professor at the Institute for Human Evolution and the School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand (PO Wits 2050, Johannesburg, South Africa [lyn.wadley@wits.ac.za]).

Innovative technologies requiring executive functions are different from technologies that use technical expertise that is normally acquired through apprenticeship (Wynn and Coolidge 2007*b*). Wynn and Coolidge caution that if expertise can produce a weapon such as a hafted spear (and it can), archaeologists should conclude that this simpler skill, rather than well-developed executive functions, was responsible. How, then, can we recognize in the deep past the presence of executive functions, abstract thought, thoughts about time, and the ability of the mind to do many things simultaneously? What behavioral proxies for these abilities would we need to recognize in the archaeological record? Long-distance and out-of-sight behavior involving response inhibition (such as setting traps) would seem to be a convincing proxy for both language and complex cognition. I shall try to convince you that other proxies exist, too. In the course of this paper, I shall analyze steps required to implement a technical strategy, in this case composite-tool manufacture using compound adhesive. I shall argue that some of the steps may have been impossible without recursion, abstraction, thoughts about past and future, and the ability to multitask. First, I examine some archaeological data.

## Some Clues from Archaeological Evidence

It is unlikely that a Rubicon for the origin of complex cognition will be found archaeologically—the process of mod-

ernizing cognition was almost certainly gradual. Some archaeologists argue that the process began at the dawn of the Middle Stone Age (MSA) about 300,000 years ago. Ambrose (2001) proposed that composite-tool making began then (based on the appearance of backed tools at this time in Zambia) and that this new behavior reflected an increase in cognitive capacity. He hypothesized that composite-tool making requires planning and coordination of multiple, segregated tasks and that these sophisticated behaviors evolved side by side with frontal lobe development. Cognigrams that describe the steps required for the production of a wooden spear, such as those found in Germany at Schoeningen 500,000–400,000 years ago (Thieme 1997), are much simpler than those describing manufacture of composite weapons (Haidle 2010). The methods involved in making a single-component spear, such as simple stone tool knapping, could be taught to apprentices through demonstration—the “string-of-beads” approach. It could also be argued (as in Wynn and Coolidge 2007*b*) that expertise was sufficient for the construction of composite tools even though these require an enormous outlay of labor for producing armatures and for hafting stone inserts (Ambrose 2001; Torrence 2002). However, I believe that this process is far more complex than previously has been recognized. As a case study, I explore the evidence for composite weaponry in stone tool industries of the MSA of South Africa—specifically at two sites: Rose Cottage Cave and Sibudu Cave—and I then describe my replications of composite tools using compound glues.

Rose Cottage Cave, in the eastern Free State, has multiple MSA layers with ages between about 26,000 and 100,000 years ago (Jacobs et al. 2008*a*; Valladas et al. 2005; Wadley 1997). Sibudu Cave, in KwaZulu-Natal, has multiple MSA layers dating between 35,000 and about 80,000 years ago (Jacobs et al. 2008*a*, 2008*b*; Wadley 2005*a*, 2006*a*; Wadley and Jacobs 2006). In a preliminary residue and use trace analysis of a variety of MSA and Later Stone Age (LSA) stone tools from Rose Cottage Cave, Williamson (1997) detected the presence of red ochre and polish marks on the bases of many of the tools where we expect that they would have been attached to handles or shafts. This alerted us to the possibility that at least some stone tools had been hafted to handles or spear shafts using ochre as an ingredient of the adhesive. Here I examine two classes of stone tools: points and segments.

### Points

Points are sufficiently common in the MSA sequence that they are often used as a defining feature of technocomplexes that lasted from about 300,000 to 25,000 years ago (McBrearty and Brooks 2000). It is widely accepted that stone points are tips of spears in both the African MSA and the European and Middle Eastern Middle Paleolithic (e.g., see Minichillo 2005; Shea 2006; Villa, Delagnes, and Wadley 2005; Villa and Lenoir 2006). Spears can be thrusting weapons or throwing weapons

(Hughes 1998). Thrusting spears are handheld, while throwing spears are flight weapons (i.e., projectiles such as javelins).

Points have a variety of base shapes and thicknesses because some were deliberately thinned to fit their shafts. All points share the need to be hafted in a single direction, with the tip at the distal end of the weapon where it can penetrate the hide of prey. Use trace analyses of Sibudu points by Lombard (2005, 2006*a*; Wadley, Williamson, and Lombard 2004) revealed clusters of minute fractures on the basal laterals of points, which implies hafting. The damage was often accompanied by plant gum/resin and other plant residues, which suggests that the hafts were wooden and that plant-based adhesive was used, sometimes together with twine. A variety of adhesive types may have been employed because ochre stains were recurrently associated with the plant residues at the bases of the points (Wadley, Williamson, and Lombard 2004; Williamson 2004). The variability among glues may imply different functions for the spearheads; for example, handheld thrusting spears need unyielding glue to allow repeated thrusts. In contrast, projected spears, such as javelins, might have been designed so that the stone tip would break within the body of the prey. This could be achieved by using brittle glue that would shatter on impact. I shall discuss glue types in more detail later. Animal product residues are concentrated on the distal ends of many of the points that Lombard (2005) analyzed, confirming that they were used as hunting weapons.

While stone-tipped spears are composite weapons because they have minimally two components—shaft and stone tip—they are not as complex as composite tools with barbs or tools with inserts that can be hafted in different directions. I now discuss a class of tools for which directionality is not constrained.

### Segments

Segments (sometimes called “crescents” or “lunates”) are defined as a portion of a circle with a curved, abruptly blunted back and a straight, sharp chord (Deacon 1984). Each end of a segment is pointed. The abrupt blunting (which is faceted in a manner that archaeologists call backed retouch) on the convex edge of segments probably assists their hafting by creating an area of friction for the firm attachment of adhesives (Lombard 2007; Nuzhnyi 2000; Phillipson 1976).

Segments make only punctuated appearances in the MSA and LSA. They have been found in the earliest Central African MSA, with an age of about 300,000 years (Barham 2002), but they are thereafter rare until much later. In southern Africa, between about 70,000 and 55,000 years ago, segments and other backed tools were the most common stone tools in an MSA industry called the Howiesons Poort. Segments from the MSA and the mid-Holocene LSA seem to have had multiple uses, including cutting (J. Deacon 1995; Wadley and Binneman 1995), and the long cutting edges of some segments make them ideal for use as knives. Large MSA segments may

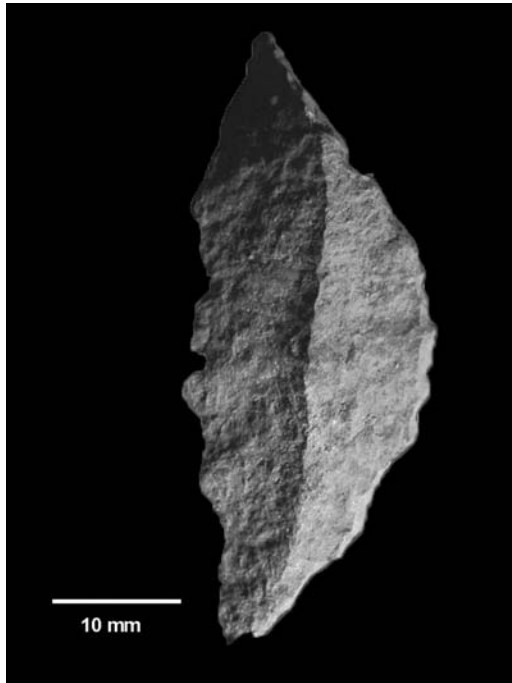


Figure 1. Dolerite segment from Sibudu showing ochre stain on its curved back.

sometimes have been used as barbs on spears or as spearheads themselves, while their small LSA counterparts may have been used as tips of arrowheads (H. J. Deacon 1995). McBrearty and Brooks (2000) and Ambrose (2001) suggest that MSA segments entail the presence of composite projectiles, although not necessarily the earliest forms of these weapons (Brooks et al. 2006). Ethnographic collections and composite weapons recovered from ancient sites show that segments and even small blades or flakes were weapon components in the past (Binneman 1994; Clark 1975; Clark, Phillips, and Staley 1974).

Residue analysis supports the suggestion that backed edges were designed to facilitate hafting because plant gum/resin, sometimes mixed with ochre or other substances, was found on the backed edges of segments and other backed tools from the Howiesons Poort industry at Rose Cottage (Gibson, Wadley, and Williamson 2004) and Sibudu (Delagnes et al. 2006; Lombard 2006*b*, 2007, 2008; fig. 1). Segments, because of their shape, with the straight cutting edge along the full length of the tool, cannot be bound with twine (the cutting edge would sever the twine), and the hafting of these stone inserts must have depended entirely on robust adhesives.

Ochre-stained segments were also found in Kenya at Enkapune Ya Muto, dated to between 50,000 and 40,000 years ago (Ambrose 1998). At Sibudu, in layers with ages somewhere between 70,000 and 61,000 years ago, Lombard (2006*b*, 2007, 2008) discovered that animal products were concentrated on the sharp, straight cutting edges of the segments,

implying that these were the working ends of the tools. Use trace analyses demonstrate that haft material was either bone or wood; furthermore, carefully mapped positions of glue residues show that segments could have been hafted in a variety of positions (Lombard 2007, 2008). By rotating a segment so that its cutting edge faces different directions, it can be hafted to form one of a variety of tools, weapons, or weapon components such as barbs. It can be hafted vertically into a lateral slot on a handle to form a knife blade. Several such insertions can form a composite sicklelike knife. Through rotation, segments can be hafted to form at least four different types of hunting weapon: (1) transverse arrowheads (with the broad cutting edges placed horizontally), (2) arrowheads or spearheads with pointed tips and asymmetrical basal barbs (with the segments placed diagonally at about 60°), (3) split-point arrowheads or spearheads (by placing two segments back-to-back), and (4) long, thin arrowheads (by placing segments vertically; fig. 2).

Replicated segments used experimentally as projectile weapons (on a carcass, not a live animal) by Pargeter (2007) demonstrated that all four of these segment rotations create satisfactory weapon tips. Transverse arrowheads were recovered in their entirety in ancient Egyptian sites (Clark 1975). The elongated shape of a segment, with the sharp cutting edge on its longest axis, suggests that it cannot be bound to its

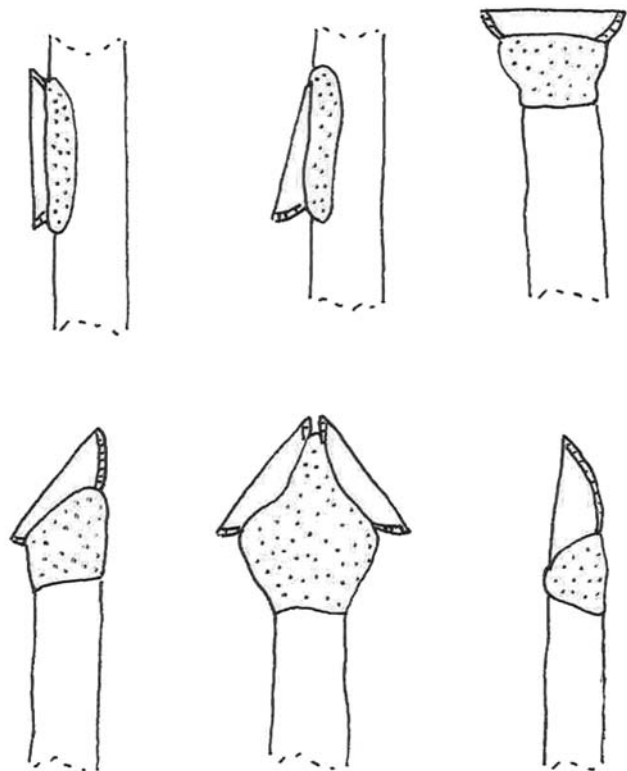


Figure 2. Six ways in which segments can be rotated for use as tools and weapons. The stippled areas represent adhesive.

shaft with twine; instead, the segment must rely on glue for its attachment. Several adhesive recipes were used on segments at Sibudu and other sites (Lombard 2007, 2008). Dolerite and hornfels segments have high proportions of ochre stains on their backed edges, suggesting that ochre was part of the plant-gum adhesive, but fat has also been observed in the mixture. In contrast, crystal-quartz-backed tools examined by Lombard seem to have been attached to their hafts using only plant gum; few of these tools have ochre on their backing (Delagnes et al. 2006:42). Of the quartz MSA segments from Umhlatuzana, another KwaZulu-Natal MSA site, 68% have plant resin adhesives but no ochre (Lombard 2007). The use of simple gum glue without additives has advantages as well as disadvantages; it is brittle and does not resist high-impact pressure (Rots 2002:57–59) and therefore allows arrow barbs or tips to become dislodged in animal carcasses, causing fatal hemorrhages (Crombé et al. 2001:260). This effect is not desirable when handheld stabbing weapons are used; here the spear's stone insert needs to remain firmly in its haft so that the hunter can, if necessary, make repeated thrusts at prey.

The results of a metric study of Sibudu segments (Wadley and Mohapi 2008) support those from use trace analyses and experimental "hunting": there are at least three separate populations of segments based on their production from quartz, hornfels, and dolerite. Attributes such as the length and breadth of segments are markedly different between the rock-type populations: quartz segments are significantly shorter, narrower, and thinner than hornfels segments, which are in turn shorter, narrower, and thinner than dolerite segments. The morphological study of Sibudu MSA segments (Wadley and Mohapi 2008) shows that the toolmakers appreciated the properties of rocks—their flaking, wear, and impact possibilities—and that they selected certain size ranges and size ratios of segments for discrete weapons.

This evidence for variable use of segments shows that they are not a single tool type other than in archaeological classification systems. The ancient artisans chose specific configurations of rocks, segment sizes, adhesives, and hafting strategies while holding in mind the desired end product. Then, through differential rotation of the segments, they were able to create an assortment of weapons and tools. Rots (2002) claims that the flexible angle at which a tool can be placed is the main advantage to hafting with adhesive. The rotation of segments was therefore made possible through the production of effective glues that did not require additional support from twine bindings around the tool.

Historical records suggest that ochre was still recently used as a loading agent for adhesives in Australia, where aborigines combine vegetal fiber and ochreous dust and sand with their resins (Rots 2002:60). Bushmen from Namaqualand, South Africa, used "euphorbid milk and red clay" as "cement" for attaching feathers to arrows, according to Doctor Atherstone, who made the observation in 1854 (Webley 1994:61). The red clay may have been ochre.

Prehistoric adhesive recipes probably varied according to

the needs of tools or weapons (Wadley 2005*b*, 2006*b*), and robust compound adhesives may not always have been desirable, even for attaching segments to their hafts. Simple plant gum creates a brittle adhesive that tends to shatter on impact. As we have seen, this is not a disadvantage when stone inserts are intended to break within the body of the prey, and some nineteenth-century South African quartz arrowheads were intended to do precisely this (Clark 1975). Plant gum may also have been preferred for attaching the tiny MSA quartz segments from Sibudu to their hafts if they were arrowheads.

Red ochre was not the only suitable loading agent for compound adhesives, and it was sometimes replaced with other ingredients such as sand. Although MSA adhesives often have ochre in them, LSA adhesives do not (Binneman 1983; Binneman and Deacon 1986; Deacon 1979; Deacon and Deacon 1980; Jerardino 2001; Mitchell 1995; Phillipson 1976; Schweitzer 1979). I now describe my replication studies with stone tools, hafts, and adhesives in an attempt to explain the complexity of decision making that seems to have been associated with the hafting of tools, particularly segments, in the MSA. The descriptions are detailed so that the reader can evaluate the cognitive requirements of the process.

## Experimental Hafting of Hunting Weapons

My experiments involved mounting stone tools on wooden handles using natural adhesives, all of which had plant gum from *Acacia karroo* as their base (Wadley 2005*b*; Wadley, Hodgskiss, and Grant 2009). Simple adhesive comprised *Acacia* gum alone; compound adhesives combined *Acacia* gum with powdered ochre and sometimes a small amount of beeswax.

### Collection of Ingredients

Replicated hafting of tools involves the collection of (1) straight sticks of a wood type suitable for handles or shafts (I used *Grewia flava*, from which Kalahari Bushmen make bows and other wooden tools, and I selected straight branches of similar thickness); (2) firewood suitable for a fire that will burn with sustained medium heat; (3) rocks for making flakes; (4) a hammer stone for knapping the flakes; (5) hematite ( $\text{Fe}_2\text{O}_3$ ) nodules for producing ochre powder; (6) coarse-grained flat rocks for grinding the ochre; (7) gum from *A. karroo* trees; and (8) *Hypoxis rigidula* leaves for twine (although twine was used on only a few tools). The collecting process from a variety of disparate sources was time consuming and involved considerable planning.

### Initial Processing of Ingredients

The initial processing of the ingredients was as follows: (1) Stone flakes were knapped, first for cutting the wooden shafts and second for making suitable sharp inserts for the weapons.

(2) Sticks were shaped to produce shafts. L-shaped platforms worked best for securely holding my stone tools, although other experiments used split shafts so that the stone could be inserted into it. The L-shaped platforms were carefully whittled to maintain right angles, and the shaft laterals were straightened and trimmed to remove nodules. The shafts were cut from wet wood. These were dried for a week so that sap would not moisten the adhesive and the shaft would not shrink after the weapon's creation. (3) Hematite nodules were ground by rubbing them on coarse stone slabs to produce powdered ochre. This is a lengthy process; about 10 mL of powder is produced per hour of grinding. About 50 mL of powder is needed for adhesive for 10 tools. Several coarse slabs are needed for the task because the grinding process is slower when the slab surface becomes smooth. Using a coarse slab is essential because tiny, angular quartz particles (80–1,000  $\mu\text{m}$ ) rub off the slab and become incorporated into the fine ochre powder. This coarse aggregate provides a variety of surface area sizes within the adhesive, and this is necessary for successful bonding, just as a variety of particle sizes creates successful concrete.

Once the ochre powder, shaped handles, and flakes were ready, the fire was lit, and the composite tool production started. I first describe the hafting of tools with *Acacia* gum.

#### *Simple Adhesives Made from Plant Gum*

*Acacia* gum is nature's own adhesive, and its role is to seal a tree's wounds. In several replications, gum was used alone (Wadley 2005b). Some of the gums were heated, and others were allowed to dry naturally. The consistency of the gum is variable; drier gums are easier to work with than runny ones, which are very sticky. Gum that is fairly dry can be molded around a tool and air-dried with no further processing. Wet gum is difficult to control, and it needs to be dehydrated over a fire to prevent it from dripping off the haft, which would cause the stone tool to fall from its haft.

Gum dries slowly, even next to a fire, and the end product is brittle, full of cracks and air bubbles, and sometimes crumbly. Like glass, gum adhesive tends to shatter on impact. *Acacia* gum is water soluble and hygroscopic; consequently, damp conditions will cause this simple adhesive to become tacky, allowing the stone tool to fall from its haft.

#### *Compound Adhesives Made with Plant Gum, Ochre, and Coarse Aggregate*

These adhesives were mixed by adding powdered ochre to *Acacia* gum (for detailed experimental results, see Wadley 2005b; Wadley, Hodgskiss, and Grant 2009). Sticky gum needs more ochre than dry gum to make it workable. When the mixture is workable, it can be easily molded to a tool. There is no recipe that can be followed; making these glues is not like baking a cake. The technique is not routine; it entails evaluating the qualities of the ingredients and adjusting their

quantities accordingly. It requires complete, undivided attention. A tiny piece of beeswax was added to a few of the adhesives, and this creates satisfying plasticity in the compound. However, a dab too much of beeswax results in an adhesive with "creep"; once dry, it shrinks and releases the stone tool from the haft.

By adding an aggregate, the artisan cuts back on the time that is required to dehydrate and harden the adhesive. Moderate heat from a fire dries and hardens the adhesive considerably faster than drying without heat. Air-dried adhesive takes a long time to set—24 hours after manufacture, a stone tool will dislodge from its haft immediately if it is used, revealing wet adhesive as a soft center inside the hardened outer crust. My experiments showed that it takes as long as 6 days for air-dried adhesive to dry and harden properly. However, tools that were slowly dried near a fire for between 3 and 4 hours (rotating them about every 10 minutes) could be used immediately without them breaking. The use of fire for dehydrating the ochre-loaded adhesive is an art, and the tools' distance from the fire must be judged carefully. On one of my first incompetent attempts at heating a newly hafted tool over the fire, the adhesive swelled and the outer crust became hard and charred, leaving an air-filled hollow under the crust. This weakened the adhesive and the stone tool fell out. When tools are heated too rapidly, the adhesive begins to boil, and this also creates cracks and weakness. Vigilance, keen judgment, and an understanding of the feel and appearance of the end product are required; failure can befall the tool at any stage of its gestation if the artisan's attention wavers.

Ochre-loaded adhesive is not water soluble or hygroscopic after it has been properly dried. A combination of gum and ochre provides an adhesive that cannot be reheated for recycling, and the components cannot be separated after they have been mixed and dried. The process is irreversible.

One clue to the success of ochre as a loading agent may be in nature: iron oxide minerals act as cementing agents in some sedimentary rocks, such as banded ironstone or conglomerates; the iron oxide is chemically deposited from solutions containing the mineral. A change in pH is part of this geological process, and after ochre is added to gum, a change in pH also takes place (Wadley, Hodgskiss, and Grant 2009). Pure synthetic hematite powder was never successful for adhesive manufacture because it lacks coarse grains. What makes concrete set successfully in a modern engineering context is the amalgamation of sand with fine and coarse stone aggregate to bind the fine, powdery particles of cement when water is added. Clearly, a similar combination of ingredients is required to create adhesive with ochre powder and gum. By grinding ochre nodules directly on coarse sandstone slabs, as I did (and similar ones have been found at Sibudu Cave), the ancient glue makers would have automatically created a coarse component in their glues. If this method was not used, sand would need to be added to make up the necessary coarse-grained aggregate.

## Are Compound Adhesives Proxies for Complex Cognition?

My adhesive replications and metric studies and the use trace analyses conducted by Lombard (2006a, 2006b, 2007), Williamson (2004), and Gibson, Wadley, and Williamson (2004) imply that artisans in the MSA had considerable technical skill. However, Early Stone Age artisans also had enviable skill (Wynn 1979, 1989), but this does not suggest that they had complex cognition. The link between technological sophistication and cognitive complexity needs to be demonstrated, not assumed. We need to show what types of mental architecture are indispensable for specific innovations.

Was it serendipitous that people 70,000 years ago got the intricate process right when they were making compound adhesives? I tend to think that it was not. Sticky *Acacia* gum, nature's own adhesive, can be used intuitively by people. However, when this simple glue became inadequate, people did not seek a more potent natural adhesive. Instead, they "renovated" their existing plant-based glue in an innovative and nonintuitive manner. In order to create compound glue with plant gum as its base, they selected a product—ochre powder—that has no gluelike attributes. Fat and wax also lack attributes of natural adhesives, and these products were sometimes mixed with gum and ochre. It could not be predicted, without considerable imagination, that the use of items with nonadhesive properties could create successful glue. We can express the transformation process, which involves a chemical reaction: loose, dry powder + sticky, wet gum + heat = hard, dry concreted adhesive. The whole is indeed greater than the sum of its parts; the whole is a marriage of the most desirable attributes of each separate ingredient. The concept of transformation is important to the production of the irreversible adhesive, and I argue that the type of thought process required to make compound adhesives is not much different from that required for technologies such as alloying metals and firing ceramics.

In some ways, the creation of compound glues mimics the combinability that characterizes modern language (Reuland 2010). Embedded recursion—necessary for linguistic dependencies—requires that material stay internally represented before and after it is realized ( $ab$ ,  $aabb$ ,  $aaabbb$ , . . .  $a^n b^n$ ). It enables the emergence of infinite combinability, but the system must hold in mind what it has previously done in order to carry out what still has to be done. Haidle (2010) claims that human manipulation of objects sometimes shows structural and cognitive parallels to language, including the use of recursion and concepts of past and future. The parallel can certainly be drawn with respect to the manufacture of compound adhesives, where there is constant feedback, reassessment, and correction of problems throughout all the stages of action. The process also involves coordinating past and future actions to ensure a successful end product. Thoughts about time—past and future—are important in modern language, as is abstraction (the ability to recognize regularities

in diversity; Reuland 2010). Among its many roles, language enables people to talk about behavioral variation, which can be abstracted, enabling innovation from the circuit.

The artisans who made compound adhesives must have understood and abstracted the individual attributes of ingredients such as plant gum and ochre, as well as the combined properties of these inorganic and organic materials. Thus, qualities such as wet, sticky, and viscous were mentally abstracted, and these meanings were counterpoised against the properties of dry, loose, and dehydrating. The second set of attributes opposes the first, but it is also remedial to it so that, in combination, the attributes are complementary. I argue that this provides an example of fourth-order abstraction as described by Barnard (2010), who makes the point that simultaneous mental processing of two levels of meaning would not have been possible before modern complex cognition. Fourth-order abstractions are schematic models of self, others, and world, and their content can be compared with generic feelings or intuition (Barnard 2010). Only the most advanced mental architecture can control walking, talking, and thinking at the same time, and this mental architecture adds the ability to reorder elements of ideas and to evaluate whether an idea is worth thinking about (Barnard 2010).

It is difficult to imagine how the expert glue maker could train an apprentice to make compound adhesives without explaining, in abstract terms, attributes and conditions such as stickiness, viscosity, workability, consistence, plasticity, texture, particle size, temperature, concretization, water solubility, hydroscopic, dehydration, reversible process, irreversible process, shrinkage, homogeneity, creep, and shrinkage. The concept of the irreversible transformation had to be explained using language as we understand it, for example, incorporating recursion, abstraction, and words to describe both the past and the future.

Executive functions—such as projecting future action, anticipating problems, and preparing responses—are implicated in the making of compound, heat-treated glues. The master glue maker would have needed to hold in mind a template for the end product because adhesive manufacture is not an exact science and there is no set recipe for success. Quantities of ingredients must be varied according to the condition of each at the time of use. Viscosity of plant gum and the texture and grain size of ochre powder must be gauged while the adhesive is being mixed in order to get the right consistency. The moisture content of gum varies from tree to tree and season to season. Ochre nodules produce powder of different grades depending on how and where the parent rock weathered. The ancient artisans also needed to understand the effects of varying temperature on their adhesives and, in turn, the temperature potentials of dissimilar woods. The process thus provides an example of Amati and Shallice's (2007) non-routine thought that aims for novel goals.

Thought experiments require holding a multiplicity of information in the mind at the same time. Not only did the makers of the MSA composite tools hold in mind the vagaries

of compound-adhesive manufacture; they also simultaneously had to think about the correct position for placing stone inserts on the hafts. By about 70,000 years ago, artisans were able to perform mental rotation of segments in order to create implements of different shapes with different objectives. The artisans needed to think abstractly about the qualities of their segments in order to visualize their use after rotation. More important, successful mental rotation seems to require advanced working-memory capacity and, in turn, complex cognition. The connection has been made by psychologists using complex span tasks that are reliable and valid psychometric tests for measuring working-memory capacity. The tasks are able to predict performance in cognitive assignments such as listening comprehension, language comprehension, following oral and spatial directions, reasoning, and hypothesis generation (Engle 2010, in this issue). Among complex span tasks used by psychologists are, for example, spatial ones requiring a person to rotate a letter mentally or decide whether a figure is symmetrical around a vertical axis (Engle 2010; Kane et al. 2004). Performance on such spatial tasks is linked to higher-order cognitive capabilities such as executive function and complex reasoning (Kane et al. 2004).

In conclusion, I maintain that compound-adhesive manufacture in southern Africa 70,000 years ago (and possibly earlier, but this has not yet been explored) required complex cognition. As is the case in recursive language, the artisan needed to hold in mind what was previously done in order to carry out what was still needed. People were able simultaneously to talk, think, mix glue, maintain fire temperature, and mentally rotate stone tools. As I have shown, some of the steps in the making of compound adhesives and composite tools are not possible without abstraction, recursion, and cognitive fluidity. Consequently, there seems to be a strong case for attributing advanced mental abilities to people who lived 70,000 years ago in Africa (and perhaps elsewhere if similar processes are discovered out of Africa).

It is not yet possible to attribute complex cognition to people who lived 300,000 years ago. In the *Zambian site* of that age, Twin Rivers, quantities of coloring materials occurred with backed tools, which Barham (2002) believes may be the earliest of their kind and may be indicative of composite tools (Ambrose 2001). It would be truly remarkable if these backed tools were hafted with compound adhesives to form many types of weapons, but there is, as yet, no evidence for this, and the backed tools may have been handheld. D'Errico's (2008; d'Errico and Soressi 2002) work at Pech de l'Azé, France, has demonstrated that there was systematic pigment use by Neanderthals, so the use of pigment itself is not species specific. Neanderthals also made use of pitch for attaching their stone tools to hafts (Boëda et al. 1996). The ingenious Neanderthal technology involved the use of controlled heat because the resin portions of birch tar do not melt below 340°C and they burn above 400°C (Koller, Baumer, and Dietrich 2001). What seems to distinguish the compound adhesives discussed here from the birch tar used by Neanderthals

is the multitasking evident in the manufacture of the *Acacia* gum and ochre compound glues. However, archaeological data are added to almost daily, and we may yet be in for surprises regarding the technological and cognitive abilities of hominids before the period under review. I suggest, however, that if other compound glues are discovered archaeologically, they should be experimentally reproduced. It is only through this kind of work that we can gain an understanding of the mental processes involved in technology.

My case study from southern Africa suggests that archaeologists working with sites from different periods and in different parts of the globe may also find it useful to analyze the mental processes implied by technologies evident at their sites. Because few archaeologists have agreed on an appropriate definition of symbolic behavior in the deep past, the type of method I offer here seems to provide a useful alternative for recognizing complex cognition.

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# Working Memory and the Speed of Life

by April Nowell

Hominin evolution is the result of complex interactions of biology and behavior within particular physical, social, and cultural environments. While evolution takes place at the species level, species are made up of individuals engaging in a social world. Extensive research into topics such as theory of mind and social intelligence have highlighted the importance of sociality and social factors in understanding the evolution of the hominin brain. The hominin brain has trebled in size throughout our evolution and has undergone significant reorganization. These changes have associated life-history costs and benefits and can be understood only in the context of alterations in hominin ranging behavior, locomotion, diet, energetic requirements, subsistence strategies, childbirth, ontological development, demography, communication/play, and technology. Many of the significant changes in these variables, as well as in cranial development, coincide with the emergence of *Homo erectus*. It is with this species that we see a clear movement away from pongid life-history patterns toward a pattern that we would eventually recognize as human. I discuss key changes in hominin life history that can reasonably be associated with *H. erectus* and the cognitive implications of these changes for an early enhancement of working memory away from ape-grade abilities.

Hominin evolution is the result of complex interactions of biology and behavior within particular physical, social, and cultural environments. While evolution takes place at the species level, species are made up of individuals engaging in a social world. More than 20 years of research into topics such as theory of mind, social intelligence (e.g., Byrne and Whiten 1988; Milton 1988; Whiten and Byrne 1997), and the social brain (Dunbar 2003) have highlighted the importance of sociality and social factors in understanding the evolution of the hominin brain. It is well established that our brain has trebled in size throughout our evolution and has undergone significant reorganization (e.g., Holloway, Broadfield, and Yuan 2004). These changes have associated life-history costs and benefits and can be understood only in the context of alterations in hominin ranging behavior, locomotion, diet, energetic requirements, subsistence strategies, childbirth, ontological development, demography, communication, and technology. Many of the significant changes in these variables, as well as in cranial development, coincide with the emergence of *Homo erectus*. It is with this species that we see a clear movement away from pongid life-history patterns toward a pattern that we would eventually recognize as human. In this paper, I discuss key changes in hominin life history that can reasonably be associated with *H. erectus* and discuss the cog-

native implications of these changes for an early enhancement of working memory (WM) away from ape-grade abilities.

Following Antón (2003), in this paper I use the term *H. erectus (sensu lato)* to refer to a polytypic, widely dispersed allotaxa (see Jolly 2001). While there is considerable temporal and geographic variation among *H. erectus* specimens, they are united “by a total morphological pattern that is shared across regions” (Antón 2003:153). This allotaxa first appears at approximately 1.8 Ma in Africa, with its youngest members surviving until 100,000 BP or even 50,000–25,000 BP in Indonesia (see discussion in Antón et al. 2007; Swisher et al. 1994). Its appearance and survival vary greatly by region. Fossil and/or archaeological sites attributed to *H. erectus* occur in Africa, Asia (including Indonesia), the Levant, and Europe. Most recently, *H. erectus* remains have been found for the first time in Turkey, bridging a temporal and geographic lacuna in our knowledge of the spread of this species (Kapelman et al. 2008).

## The Speed of Life

Life history is sometimes referred to as reproductive turnover or “the speed of life” (Stearns 1992). Following this metaphor, it is often said that primates have the slowest life histories of all the mammals (Harvey and Clutton-Brock 1985; Robson and Wood 2008; Zimmermann and Radespiel 2007), and by extension, one might infer that humans experience the slowest life histories of all the primates. But the emerging picture of human life history is at once more complex and more elegant.

**April Nowell** is Associate Professor of Archaeology in the Department of Anthropology at the University of Victoria (Victoria, British Columbia V8W 3P5, Canada [anowell@uvic.ca]).

Dean and Smith (2009) define life history as “the allocation of an organism’s energy for growth, maintenance and reproduction . . . it is fundamentally a life strategy adopted by an organism to maximize fitness in a world of limited energy” (115). Robson and Wood (2008:396) distinguish between life-history variables that directly “reflect population vital rates and timing of life history events” but that cannot be measured directly in fossil species—such as gestation length, age at weaning, interbirth interval, and age at first and last reproduction—and life-history-related variables. These variables have “been shown empirically with extant primates to be constrained by or correlated with [life-history variables]” and include adult and neonatal body mass, adult and neonatal brain mass, dental crown root formation times, and dental eruption times (Robson and Wood 2008:396). This latter set of variables can potentially be derived from the fossil record and are used to make inferences regarding the former suite of variables (Robson and Wood 2008; see also Bogin 2003; Harvey and Clutton-Brock 1985).

As paleoanthropologists, we are accustomed to thinking in terms of k-strategists and r-strategists. Relative to r-strategists, k-strategists reach the age of reproduction more slowly, have fewer offspring, and put greater investment in each offspring. While k-strategists are thought to produce “high quality offspring that are larger, smarter or more social,” the drawback to being a slow reproducer is that you risk dying before you reproduce (Dean and Smith 2009:101; Robson and Wood 2008). But humans are unique in that they have elements of an r-strategy within the larger life history of a k-strategist. Specifically, they have a long gestation period and a large brain, they mature slowly, with females reaching the age of reproduction later; they experience an extended dependency period; and they enjoy increased longevity. However, at the same time, they have evolved shorter birth spacing, they wean sooner, and they have more dependents than expected for an ape that matures at the age modern humans do (Robson and Wood 2008). Essentially, modern humans are characterized by a reproductive pattern “that works in double time compared to our closest relatives, the great apes” (Dean and Smith 2009:115)—something that Wood (1994) has described as secondary r-selection. Added to this unique combination of features are a suite of derived elements—concealed ovulation, helpless young, paternal care, vigorous postmenopausal life in females, and grandmothing (see below; Dean and Smith 2009:115; Hawkes, O’Connell, and Blurton-Jones 2003; Kaplan 2002; Robson and Wood 2008; Zimmermann and Radespiel 2007). Thus, modern humans have developed a strategy of producing high-quality offspring while at the same time reducing the risk of dying before maturation by “living fast” in some respects within an overall pattern of “living slow.” According to Dean and Smith (2009), “Much of what makes our life history unique took shape during the evolution of the genus *Homo*” (101).

## Working Memory

The emergence of *Homo erectus* represents a turning point in hominin evolution because many of the key shifts from an apelike to a humanlike pattern of life history occur with this species. These shifts have important implications for cognitive abilities associated with the evolution of WM. WM is normally divided into a central executive system that is concerned with higher-level reasoning; two subsystems consisting of a visuo-spatial sketch pad for the temporary storage and integration of visual and spatial information and a phonological loop consisting of brief sound-based storage and a processor that maintains information through vocal and subvocal rehearsal; and an episodic buffer integrating the two subsystems (Coolidge and Wynn 2005, 2007; Read 2008; Wynn and Coolidge 2003, 2004).

When we draw on Casey, Giedd, and Thomas (2000) and Coolidge and Wynn (2005, 2007), WM is involved in interference control (the ability to override competing attentional or behavioral responses), inhibition (the ability to resist competing behavior, memories, or responses), sequential memory, temporal-order memory, and the integration of information across space and time. These are all necessary for sequencing activities in their proper order to attain a goal (Coolidge and Wynn 2005, 2007). Furthermore, WM is correlated with other abilities such as emotional reasoning, storytelling, general intelligence, and fluid intelligence (the ability to solve novel problems; Wynn and Coolidge 2010, in this issue). Thus, increased WM capacity would have conveyed huge advantages to our hominin ancestors compared with other species, and it appears to have been selected for throughout our evolution. For instance, the central executive, associated with Brodman’s areas 4 and 9 in the dorsolateral section of the prefrontal cortex, has undergone significant expansion since the human-ape divergence, suggesting to scientists that the capacity for WM has increased accordingly (Read 2008; Schoenemann 2006).

## Life-History Changes in *Homo erectus*

The relationship between the changes in life history that can be reasonably attributed to *Homo erectus* and WM will be now be considered. The following suite of features represents a complex biobehavioral adaptive package that begins in the late Pliocene.

### *Increasing Cranial Capacity and the Cranial Reorganization*

*Homo erectus* is characterized by a 20%–60% increase in brain size relative to early *Homo*. The brain is an expensive organ to support and would require a significant alteration of diet (see below). In *H. erectus*, the brain would have required 17% of an individual hominin’s resting energy compared to 11% for australopithecines (Antón 2003). Further energetic costs would be incurred by *H. erectus* females both during preg-

nancy and lactation and in relation to decreased locomotor efficiency in females due to a broadening of the pelvis to accommodate larger-brained infants (Aiello and Key 2002; Aiello and Wells 2002).

In terms of reorganizational changes, between approximately 3.5 and 2.0 Ma, the paleoneurological evidence suggests that *Australopithecus afarensis* and *Australopithecus africanus* underwent a reduction of the primary visual striate cortex, area 17, and a relative increase in the posterior parietal cortex (Holloway, Broadfield, and Yuan 2004). It is with early *Homo* and *H. erectus*, though, that we begin to see changes in the frontal and prefrontal lobes, key sites for WM. On the basis of studies of the KNM-ER 1470 endocast and Indonesian *H. erectus* endocasts by 2.0–1.8 million years ago, there is evidence of a reorganization of the frontal lobe (third inferior frontal convolution, Broca's area, and widening of the prefrontal), cerebral asymmetries, and left occipital–right frontal petalias (Holloway, Broadfield, and Yuan 2004). Starting at 1.5 Ma, researchers observe in *H. erectus*, archaic *sapiens* (*sensu lato*), Neanderthals, and anatomically modern human populations refinements in cortical organization to a modern human pattern (Holloway, Broadfield, and Yuan 2004, tables 2, 3). Specifically, while emphasizing the limitations of their sample size, Holloway and colleagues (Holloway, Broadfield, and Yuan 2004) argue that “*Homo erectus* and subsequent fossil hominins clearly show cerebral asymmetries and Broca's cap regions of modern human form. . . . If these conclusions, drawn from the paleoneurological and other cranial and post cranial evidence are correct, most of the important reorganizational changes were complete by between 1.5 and 2.0 MYA” (287–288). I will return to this point in relation to *H. erectus* ontogenetic development.

#### *Aided Births, Weaning, and Slowed Ontological Development*

The observed significant increase in brain size, along with an increase in body size (discussed below) and a widening of the shoulders, has led some researchers to argue that unlike non-human primates, *H. erectus* females may have required help when giving birth. This is referred to as “obligate midwifery” (Trevathan 1987; Trevathan and Rosenberg 2000). Furthermore, others have suggested that because of this increase in brain and body size in conjunction with constraints imposed by bipedalism, *H. erectus* infants would have been born relatively helpless (secondarily altricial; Jolly 1972, 1999, 2003; Rosenberg 1992; Trevathan 1987; see also Walrath 2003 and comments therein; but see Krovitz, Thompson, and Nelson 2003). A recent study of a mostly complete *H. erectus* female pelvis dating to between 0.9 and 1.48 Ma (Simpson et al. 2008) estimates that *H. erectus* neonatal brain size was approximately 35% of adult *H. erectus* brain size, falling between chimpanzee (40%) and modern human (28%) neonate brain sizes as a percentage of adult brain size. Studies of this pelvis and the revised age of 0.5–1.5 years old for the Mojokerto child (Coqueugniot et al. 2004) lead Simpson et al. (2008) to

conclude that “*H. erectus* had a prenatal brain growth rate similar to that of humans but a postnatal brain and somatic growth rate intermediate between that of chimpanzees and humans” (1090).

It is important to note that the Mojokerto child's teeth have not preserved and that because age estimates based on suture closure are considered unreliable (Balzeau, Grimaud-Hervé, and Jacob 2005), there is enormous variation in the range of ages suggested for this specimen—from less than 1 year to 6 years old—and it is possible that this revised age estimate is incorrect (Balzeau, Grimaud-Hervé, and Jacob 2005; Leigh 2006). Choosing one or another age would have important implications for our understanding of postnatal brain growth in *H. erectus*. Nonetheless, in a study of Coqueugniot et al.'s (2004) results, Leigh (2006) argues that if the revised age estimate is correct, then “analyses of absolute brain size growth reveal comparable early growth patterns in *Homo*. . . . Mojokerto's proportional brain size is consistent with proportional brain sizes in *H. sapiens* children as young as 10 months of age. Rapid early brain growth may have emerged quite early in human evolutionary history. Moreover, secondary altriciality may also have evolved early, with attendant similarities between *H. erectus* and *H. sapiens* in terms of maternal metabolic costs” (107–108), thus supporting the original contentions of Trevathan, Rosenberg, and others.

Kennedy (2003), drawing on the fact that “brain size and body size have significant correlations with a variety of maturational processes such as age at sexual maturity, maternal age at first birth and gestation length” (549), has argued that Middle Pleistocene species reached sexual maturity by approximately age 13 and that females would first give birth somewhere between 15 and 16.5 years of age. This is within the range of modern humans. Hemmer (2007, table 19.14) and O'Connell, Hawkes, and Blurton-Jones (1999:469) present very similar estimates. These age estimates are intriguing, but we must be cautious when drawing inferences from them because they are not directly testable.

An issue related to childbirth is weaning. According to a recent study by Kennedy (2005), while apes generally wean their offspring between 5.5 and 7 years of age, contemporary and even historic populations of modern humans wean their children on average at 2.5 years of age (see also Robson and Wood 2008). Although there are many cultural factors that come into play regarding weaning times (Baxter 2008), Kennedy (2005) argues that the uniquely rapid pattern of brain growth that human neonates/infants experience can be sustained on mother's milk alone for only the first year or so and that after that, the introduction of nutritious weaning foods is crucial to the development of human brain. Thus, even though early weaning is potentially more dangerous for infants, Kennedy (2005) maintains that it is the result of selection for intellectual development over infant survival. She places the gradual shift toward the human pattern of weaning around 2.5 Ma and believes it was likely in place by the origin of *H. erectus*.

Weaning leads to a discussion of another notable life-history change. It may be with *H. erectus* that female life expectancy first extended beyond reproductive senescence (menopause; Aiello and Key 2002; Bogin and Smith 1996; O'Connell, Hawkes, and Blurton-Jones 1999; see also Robson and Wood 2008). The development of a "vigorous" post-menopausal phase of life (Robson and Wood 2008) among *H. erectus* females has been linked to the so-called grandmother hypothesis. Advocates of this hypothesis posit that grandmothers and great aunts were involved in provisioning young children. This pattern of behavior would have been selected for because it allows offspring to be weaned sooner and decreases a mother's interbirth spacing, thereby increasing the overall fecundity of the species (Hawkes 2003; Hawkes, O'Connell, and Blurton-Jones 1997, 2003; Hawkes et al. 1998; O'Connell, Hawkes, and Blurton-Jones 1999; Robson and Wood 2008; but see Monge and Mann 2007).

This hypothesis is both controversial and difficult to test (see Antón 2003). Recent studies highlight the dearth of fossil evidence supporting it, suggesting instead greater paternal investment in the care of offspring (Krovitz, Thompson, and Nelson 2003). Theoretically, all primates can experience menopause (or the cessation of menses) if they live sufficiently long, but usually somatic senescence and reproductive senescence are correlated (Robson and Wood 2008). Thus, what is "derived in modern humans is not an unusual rate and thus an unusual timing of reproductive decline but a slowed rate of somatic aging, a distinctively low adult mortality rate, and in females, a vigorous post menopausal life" (Robson and Wood 2008:401). Krovitz and colleagues (Krovitz, Thompson, and Nelson 2003) argue that in order for the grandmother hypothesis to be viable, life expectancy would have to have exceeded 50 years (see O'Connell, Hawkes, and Blurton-Jones 1999:469; see also Robson and Wood 2008). On the basis of body size and brain weight (estimated from cranial capacity), it is predicted that *H. erectus* individuals were living until their late 50s (Hemmer 2007, table 19.14) or even into their 60s (Bogin and Smith 1996).

Demographic data, however, from Sima de los Huesos at Atepuerca, Spain, a population of "pre-Neanderthals," indicate that life expectancy for these hominins was a maximum of 40 years, with most females dying between the ages of 16 and 20 and with none surviving past 30 years of age (Bermúdez de Castro and Nicolás 1997 as cited in Krovitz, Thompson, and Nelson 2003). Similar mortality data characterize Neanderthals. In some studies, 80% of Neanderthals die before the age of 40 (Trinkaus 1995). It is a question of how representative these samples are, but for Krovitz, Thompson, and Nelson (2003), it makes it less likely that life expectancy in *H. erectus* populations significantly exceeded those of subsequent species. In this context, Dmanisi 3900, the edentulous *H. erectus* mandible, with its associated cranium (3444) dating to 1.77 Ma, is relevant. This specimen exhibits almost total maxillary and mandibular alveolar resorption due to tooth loss that surpasses even the La Chapelle-aux-Saints

Neanderthal (Van Arsdale 2006). These observations, in conjunction with the extreme wear and fragility of the surrounding bone, suggest that this might be a very old individual. Similarly, O'Connell, Hawkes, and Blurton-Jones (1999 and references therein) argue that taphonomic and forensic studies demonstrate that (1) elderly individuals are less likely to preserve because of bone mineral depletion and (2) age estimates of adults over the age of 25 based on the skeleton are known to dramatically underestimate their true ages.

In sum, the pattern of "living fast" in terms of reproduction and "living slow" with regard to life expectancy and ontogeny is beginning to emerge with *H. erectus* relative to earlier specimens (O'Connell, Hawkes, and Blurton-Jones 1999), although it may not yet be at the rate of modern humans (e.g., Antón et al. 2007; Dean and Smith 2009; Dean et al. 2001; see also Simpson et al. 2008). Nonetheless, the changes represent a shift toward the human condition and have important implications for WM.

#### *Life-History Stages, WM, and Play*

Human biologists divide human life history into five stages: infancy (birth to weaning), childhood (weaning to eruption of M1), juvenile, adolescence, and adulthood, with childhood and adolescence being unique to humans (Bogin 2003). There is general consensus that the life histories of *H. erectus* included either a childhood stage for the first time or at least a significantly expanded childhood (Bogin 2003; Krovitz, Thompson, and Nelson 2003). This is significant because childhood conveys two specific advantages. First, because "the timing of major life history events tends to be correlated . . . [with] a shift in the timing of one event result[ing] in a concordant extension or compression in the span between the occurrence of other events" (Robson and Wood 2008: 395), the development of a childhood stage led to a shortening of the infancy period in humans when females are lactating. This means that females more quickly become fertile again, resulting in shorter birth intervals (Aiello and Key 2002; Bogin 2003). Second, Bogin (2003) notes that "the human childhood stage adds an additional four years of relatively slow growth and allows for behavioral experience that further enhances developmental plasticity" (32). On the basis of measurements of the facial skeleton, Antón and Leigh (2003) suggest that *H. erectus* experienced a limited adolescent growth spurt (see also Dean and Smith 2009; Tardieu 1998). Because the adolescence stage provides additional years of development that are necessary to "learn and practice technology, social organization, language and other aspects of culture" (Bogin 2003: 32; Kaplan et al. 2000), the further evidence for a slowing life history among *H. erectus* is significant. A greater percentage of offspring reach adulthood in mammals that have juvenile periods than in species without this stage. By extension, the additional amount of learning time afforded by the childhood and adolescence stages should have dramatically enhanced offspring survival (see also Nowell and White 2010).

This is particularly relevant because it is during early and late childhood that milestones in social and cognitive learning are reached (Casey, Giedd, and Thomas 2000). It is also during adolescence that “high demands are placed not only on the executive systems but also on the interplay between cognitive and emotion-related processes. Such cognitive-emotion interactions are particularly crucial in the context of peer-peer interactions and the processing of verbal and nonverbal cues” (Paus 2005:64).

The dorsolateral prefrontal cortex, the region most closely associated with WM, is the last region of the brain to mature and develop (Casey, Giedd, and Thomas 2000; Durston and Casey 2006; Paus 2005; Vuontela et al. 2003). Specifically, through late childhood and into adolescence, there is a gradual decrease in synaptic density in the prefrontal cortex, with concomitant strengthening of the remaining synapses (Casey, Giedd, and Thomas 2000). This is completely different from other areas of the cortex, such as the visual cortex (Casey, Giedd, and Thomas 2000). This plateauing and pruning of synapses in the prefrontal cortex probably represents “the behavioral, and ultimately, the physiological suppression of competing, irrelevant behaviors” (Casey, Giedd, and Thomas 2000:246). Data from pediatric functional magnetic resonance imaging studies of prefrontal cortical activity suggest that attention, memory, and inhibition—all key elements of WM—continue to develop during childhood and adolescence (Casey, Giedd, and Thomas 2000).

In a study involving weanling rats, one group of young rats was housed and reared with one peer, another group had access to three peers, and a third group had only an adult female for company (Pellis and Pellis 2009). All three groups of weanlings were exposed to normal socialization except that the latter group would not engage in play because it is rare for adult rats to play with juveniles—even with their own offspring. Autopsies conducted on the rats’ brains revealed that the major difference between the three groups was in the development of the prefrontal cortex. Specifically, there was greater synaptic density in the medial prefrontal cortex of rats that were prevented from interacting with members of their peer group than in the groups that were permitted such interaction (Pellis and Pellis 2009). In other words, that all-important pruning did not take place. This study provides the first direct evidence that play deprivation actually altered the “anatomy of the neurons,” leading Pellis and Pellis (2009: 92, 94) to conclude that “the brain not only shapes play but that play shapes the brain.”

In all mammals, interaction with peers—play—is key to socialization. It is during play that individuals establish social relationships, learn about their environment, problem solve, hone skills they will need for survival, and learn to cope with stressful situations. Pellis and Pellis (2009) observed that “play deprivation leads to a reduction in the ability of the animal to formulate and engage behavioral options dependent on the executive functions of the prefrontal cortex” (92). They found that play deprivation resulted in the same difficulties exper-

rienced by animals that were raised normally but that had their prefrontal cortex damaged experimentally. On the basis of the data as we currently understand them, if it is reasonable to infer that the pace of ontological development, while not at the rate of modern humans, had certainly slowed with *H. erectus*, then the implications of an extended childhood and possibly even adolescence are enormous. There would have been increased time for the development and maturation of the dorsolateral prefrontal cortex—for the pruning of irrelevant behaviors and the strengthening of others through the development of memory (and the ability to draw on past experiences), inhibition, and attention. At the same time, these new life-history stages would have allowed for increased interaction with peers through play. Play is the behavioral correlate of these cortical changes—it is during play that certain behaviors are reinforced and others are suppressed. This, as we shall see, is reflected in the ability of *H. erectus* to be ground sleepers, to share meat and other food, to engage in persistence hunting, and to make cognitively more complex stone tools, and these behaviors are possible only in the context of and in relation to many other changes taking place at this time, including the transition to obligate bipedality, the expansion of day and home ranges, changing body size and energetic requirements, and concomitant dietary shifts and related subsistence strategies.

#### *Climatic Change, Expansion of Geographic Range, and the Importance of Cooperation*

*Homo erectus* is the first hominin species to leave Africa and to experience a significant expansion of its geographic range. This expansion is related to climatic change, altering ecosystems, greater flexibility in habitat tolerance and foraging repertoire, increasing energetic requirements, and alterations in locomotion (Antón 2003; Antón, Leonard, and Robertson 2002; Antón and Swisher 2004; Antón et al. 2007; Bennett et al. 2009; Lieberman et al. 2009; see also Pobiner et al. 2008). The Pliocene is characterized by an overall drying and cooling trend. After 2.5 Ma and especially by the commencement of the Pleistocene at 1.75 Ma, there is a notable shift to drier, more open habitats with C<sub>4</sub> grasses and increased seasonality and patchiness of resource distribution (Aiello and Key 2002; Unger, Grine, and Teaford 2006). This shift from mesic to xeric conditions provided more niches for terrestrial herbivores (Antón 2003; Antón, Leonard, and Robertson 2002).

As a result, this climatic trend has important implications for dietary shifts (discussed below) and coincides with the earliest appearance of hominins outside of Africa. *Homo erectus* dates to 1.77 Ma in the Republic of Georgia at the site of Dmanisi in the Caucasus mountains (Gabunia et al. 2000) and to 1.81 and 1.66 Ma in Java at the sites of Mojokerto and Sangiran, respectively (Larick et al. 2001; Swisher 1997; Swisher et al. 1994). Early evidence of *H. erectus* in the Levant is less certain. While stone tools have been recovered from two Jordan Valley sites, ‘Ubeideiya (1.4 Ma) and Erq el-Ahmar

(1.9–1.8 Ma; Antón and Swisher 2004; Bar-Yosef and Goren-Inbar 1993; Ron and Levi 2001), only at ‘Ubeideiya are the stone tools in association with hominin remains (fragments of cranial vault and teeth), and these are undiagnostic at the species level (Antón and Swisher 2004; Bar-Yosef and Goren-Inbar 1993).

Antón and colleagues (Antón, Aziz, and Zaim 2001; see also Antón 2003), using diffusion coefficients based on site locations, dates, and changes in home range size (based on body size estimates from fossils), suggest that *H. erectus* experienced a rapid rate of dispersal from Africa into Asia following dispersing herbivores as part of an interchange of fauna between Africa and Eurasia (Antón, Leonard, and Robertson 2002 and references therein). It is also important to note that geographic barriers such as the Sahara Desert did not exist during the late Pliocene/early Pleistocene (Antón, Leonard, and Robertson 2002). As Antón, Leonard, and Robertson (2002) observe, “Changes in foraging strategy, body size, and ecosystem structure [led] to increases in [home range] size thus enhancing [the] dispersal capability of early African *H. erectus* over that of earlier [hominins]” (782; see also Bennett et al. 2009). O’Connell, Hawkes, and Blurton-Jones (1999:475) argue that an extensive amount of cooperation would have been necessary to allow for range expansion into new and varied ecological settings. Specifically, they posit that *H. erectus* was able to exploit a wide range of habitats because there was a “relaxation of the limits previously imposed on adult foraging by children’s resource handling capabilities” (O’Connell, Hawkes, and Blurton-Jones 1999:475) due to increased provisioning of children by grandmothers. Even though the role of grandmothers in *H. erectus* society is controversial, it is likely that there was strong selection pressure on greater societal cooperation in order to facilitate rapid range expansion into unfamiliar and varied new territories.

#### *Obligate Bipedalism, Endurance Running, and the Transition to Ground Sleeping*

On the basis of anatomical data, *H. erectus* is the first obligate biped. Whereas the australopithecines and, most likely, early *Homo* were spending at least part of their time in trees, perhaps sleeping in nests at night for safety from predators (Sabater Pi, Veà, and Serrallonga 1997), *H. erectus* is fully committed to ground dwelling. In fact, as Steudel-Numbers and Wall-Scheffler (2009) observe, “The earliest we see body mass and locomotor morphology similar to that of modern humans is among certain populations of *H. erectus*” (357). Newly discovered footprints attributed to *H. erectus* at the site of Ileret in Kenya (Bennett et al. 2009) further support this assertion. Researchers describe the 1.5-Ma footprints as the “earliest evidence of a relatively modern human-like foot with an adducted hallux, a medial longitudinal arch, and medial weight transfer before push-off” (Bennett et al. 2009:1201).

Lieberman et al. (2009) argue that while some derived fea-

tures of *H. erectus* are the result of selection for *both* long-distance walking and long-distance running—suggesting that “*Homo erectus* was the first hominin with a substantially expanded day range” (82)—others can be understood only in the context of selection for endurance running, which is a derived feature in hominins. For example, there are key changes to the trunk and to the shoulder and neck area to keep the trunk and head stabilized during running, and “diameters of the anterior and posterior semicircular canals [have increased in size] relative to body mass making [them more sensitive] to head pitching accelerations” (Lieberman et al. 2009:81). It may be that there was a trade-off between arboreality and endurance running, as Lieberman et al. (2009) note: “Many ancestral features of australopithecines that improve climbing performance . . . do not conflict with the biomechanical demands of walking, but may impede the ability to stabilize the head. Selection for running capabilities may thus have selected against arboreal capabilities in *Homo*” (82). Endurance running is particularly well suited for scavenging and/or persistence hunting in the open habitats that were developing sometime around 2.0 Ma (Lieberman et al. 2009).

Ground dwelling probably included sleeping in the open, which would have left them more vulnerable to predators. This transition would have required significant alterations in interpersonal relationships and social roles with regard to communal space, altruism, and cooperation. Cognitively, this transition necessitated reciprocal understanding and the inhibition of one’s immediate needs, which is a key component of WM. For overall group safety, some individuals may have had to take on the role of sentry and would have had to delay gratification of their own need for sleep.

#### *Body Size and Energetic Requirements of Female Homo erectus*

*Homo erectus* had body proportions that included limb size within or exceeding the modern human range (Rightmire 1990; see also Bennett et al. 2009). This fact has important ramifications for overall locomotor efficiency, life history, and ranging behavior (home range size; Antón 2003). Increasing body size in *H. erectus* is considered to be a response to the shifting climatic conditions of the middle Pliocene and early Pleistocene described above (Antón 2003). What is most interesting is that this overall increase in body size is differentially accounted for by *H. erectus* females. According to O’Connell, Hawkes, and Blurton-Jones (1999), while body size for *H. erectus* as a species as a whole increases by 55%, *H. erectus* female body size increases by 70%. Thus, sexual dimorphism decreases in this species relative to australopithecines and early *Homo*, while the energetic requirements of *H. erectus* females increases more dramatically than for males (Aiello and Key 2002; see also Robson and Wood 2008), relative to earlier hominins. This increase in female body size and energetic requirements is primarily related to gestating and lactating larger-brained infants (see below; Aiello and Key

2002; Aiello and Wells 2002; Antón 2003) and would have required a higher-quality diet, specifically, one rich in essential fatty acids and amino acids (Antón 2003).

### Dietary Shifts

The dispersal from Africa, documented increases in brain and body size, the lessening of sexual dimorphism, and the differential energetic requirements of *H. erectus* females are correlates of significant shifts in diet. There is general consensus that increased acquisition of meat and marrow was crucial to supporting these changes in hominin life history (but see O'Connell, Hawkes, and Blurton-Jones 1999). While fruits, vegetables, and insects probably remained important, meat and marrow became keystone foods (Unger, Grine, and Teaford 2006). Meat would provide a large number of calories in an easily digestible form that could be used to support the increasing demands of a larger brain. Furthermore, as Unger, Grine, and Teaford (2006) note, "Animal fat would also provide important nutrients such as long-chain polyunsaturated fatty acids used to form brain tissue" (221).

Fossil, biological, and archaeological evidence attest to this dietary shift. There is a decrease in gut size (as evidenced by pelvic narrowing) due to the lessening need to process vegetal foods (Aiello and Wheeler 1995). Furthermore, it is believed that a decreased gut could offset the increased expense of a larger brain (Aiello and Wheeler 1995). There is a concomitant decrease in the size of muscles associated with chewing and in tooth size. There is a higher occurrence of small pitting on *H. erectus* teeth that may indicate that they were consuming soft but tough-to-process foods (Unger, Grine, and Teaford 2006:221). They also had thinner enamel, which suggests that they had an improved ability to slice and shear tough foods, including meat (Unger, Grine, and Teaford 2006). At Koobi Fora, a pathological *H. erectus* specimen dating to 1.6 Ma (KNM-ER 1808) seems to have suffered from chronic hypervitaminosis A. This may have been caused by consuming too much carnivore liver (Walker, Zimmerman, and Leakey 1982; see also Pobiner et al. 2008).

Molecular phylogenies of two tapeworms that are most closely related to hominins show that they diverged between 1.7 and 0.8 Ma (Hoberg et al. 2001). Because they are host specific, it suggests that *H. erectus* was eating from the same prey carcasses as carnivores by this time (Antón 2003; Hoberg et al. 2001; Pobiner et al. 2008).

The location, number, and relative frequency of cut marks on animal bones from a number of sites is consistent with butchering, defleshing, tongue removal, and marrow extraction (e.g., Pobiner et al. 2008). In many cases, *H. erectus* had access to fleshy carcasses, thus demonstrating that either they were hunting or they were primary (early-access) scavengers (e.g., Shipman 1986; Shipman and Walker 1989). Further archaeological evidence of animal processing comes from experimental research and use-wear analysis (see discussion in Nowell and Chang 2009) on Acheulian stone tools (see be-

low). Bone element composition at sites suggests that in some cases *H. erectus* transported carcasses (e.g., Pobiner et al. 2008).

There are several behavioral correlates associated with meat eating. Ethnographic data support a link between hunting, food sharing, and social cohesion because food sharing is thought to reduce the risk of starvation (Unger, Grine, and Teaford 2006 and references therein; see also Isaac 1978; Lieberman et al. 2009). Meat eating may also be further support for sex-based role differentiation (Unger, Grine, and Teaford 2006; but see Stiner and Kuhn 2006). Similarly, Eaton and colleagues (Eaton, Eaton, and Cordain 2002) argue that as hunting and/or scavenging took on a more important role in *H. erectus* subsistence strategies, it led to increasingly complex interpersonal and social interactions. They argue that these social factors in conjunction with the properties of animal fat created the necessary "psychonutritional" basis that allowed for brain expansion. Hunting and/or early-access scavenging involves coming into direct competition with other carnivores/scavengers (Shipman 1986), requiring hominins to "monopolize . . . areas on the landscape for carcass processing" (Pobiner et al. 2008:122). The transportation and possible sharing of carcasses would further necessitate an inhibition of the prepotent response. There would also be the need to coordinate resources on the landscape; as Pobiner et al. (2008) note, areas may have had shade and water but not a nearby source of raw material.

The creation of a mental map and the ability to stay on task—in other words, interference control—would be important correlates of an initial enhancement of WM in *H. erectus*. This may be especially true if Lieberman et al. (2009) are correct in their hypothesis that *H. erectus* was the first hominin to engage in persistence hunting. Persistence hunting is a "form of pursuit hunting in which humans use [endurance running] during the midday heat to drive animals into hyperthermia and exhaustion so they can be easily killed" (Lieberman et al. 2009:85). This hunting strategy was likely used opportunistically in conjunction with scavenging and/or other types of hunting. Ethnographically, we know that persistence running has a high success rate (modern hunters are successful 50% of the time, yielding 70% more meat) and low energy cost (humans are efficient endurance runners), and it would be particularly useful before the invention of weapons that could travel long distances, such as the bow and arrow. It is also well suited to the human ability to thermoregulate (Lieberman et al. 2009 and references therein). It would require, however, by definition, persistence and the ability to stay on task in order to successfully track an animal when it is no longer in sight.

In sum, *H. erectus* appears to have been able to eat a broad range of foods, including meat and marrow; Joordens et al. (2009) suggest that *H. erectus* might even have consumed aquatic resources at sites such as Trinil in Java. Such a flexible foraging strategy would promote habitat tolerance (including shifts into new habitats) and would be an advantage in a



variable, highly seasonal environment made up of microhabitats (Unger, Grine, and Teaford 2006). Interference control/attention, inhibition, temporal-order memory, the ability to call on past memories/experience, and the ability to integrate information over space and time are all components of WM that would be essential to these varied subsistence activities.

*Evidence for the More Regular Use of Fire and the Possible Evolutionary Significance of Cooking*

It is suggested by some researchers that *H. erectus* engaged in more regular use of fire for warmth, to facilitate migration into new habitats, to drive off predators, to extend the daylight hours, and, perhaps most important, for cooking (e.g., O'Connell, Hawkes, and Blurton-Jones 1999:474). Cooking would rid underground storage organs of toxins (Aiello and Wheeler 1995; O'Connell, Hawkes, and Blurton-Jones 1999; Wrangham 2006; Wrangham et al. 1999 and comments therein) and make food items, including meat, more digestible. Carmody and Wrangham (2009) argue that the increased energetic requirements of *H. erectus* were met not by meat eating per se but rather, for the first time in hominin evolution, by the regular cooking of plants and animal protein and fat. This hypothesis, they believe, is compatible with the observed reduction in tooth size, gut size, and chewing muscles and lessened masticatory strain as evidenced by facial shortening (Carmody and Wrangham 2009). Furthermore, comparative nutritional studies conducted among raw foodists, vegetarians who eat cooked foods, and people who eat a mixed (omnivorous) diet demonstrate that there is a greater difference in energy uptake between those who cook their food and those who do not than there is between those who incorporate meat into their diet and those who follow a strictly vegetarian regime (Carmody and Wrangham 2009 and references therein). They argue not only that cooking more generally provides "critical energetic benefits beyond those afforded by nonthermal processing alone" (Carmody and Wrangham 2009:388) but also that it specifically increases the energy available from meat by increasing palatability (texture and flavor), "rendering proteins more digestible through denaturation, lowering the cost of digestion through food softening, and reducing immune upregulation by eliminating food borne pathogens" (Carmody and Wrangham 2009:386).

The evidence for early fire use and, by extension, cooking, particularly before 1.0 Ma, however, is still quite scarce (e.g., James 1989; Wrangham 2006). Goren-Inbar and colleagues (Goren-Inbar et al. 2004) have recently published evidence of the controlled use of fire by *H. erectus* in Israel by 790,000 BP. They uncovered burned artifacts in a very limited area suggesting a hearth. In Europe, Gowlett (2006) notes that fire use is widespread by approximately 400,000 BP but not earlier. He hypothesizes that an increase in pyrotechnical ability is part of a larger change in intellectual and social capability that occurs at this time. This date makes it unclear whether this behavioral transition in Europe is associated with *H.*

*erectus* or a type of archaic *H. sapiens* (*sensu lato*) such as *H. heidelbergensis*.

*Paleodemography, Vocal Communication, and the Evidence for Symbolic Behavior*

*Homo erectus* social groups are estimated by Aiello and Dunbar (1993) to be just over 100 people (a 20%–25% increase over early *Homo* group size), and as a result, some paleo-anthropologists argue for increased complexity in vocal communication. In fact, Holloway and colleagues (Holloway, Broadfield, and Yuan 2004) observe that there is nothing about the paleoneurological evidence that precludes language abilities in *H. erectus* and subsequent species (see also Schoenemann 2006:390). At the same time, a recent study of the only known *H. erectus* hyoid bone suggests that the species did *not* have the capacity for human speech (Capasso, Michetti, and D'Anastasio 2008). Specifically, Capasso and colleagues observe that the 400,000-year-old hyoid from an *H. erectus* male found at the site of Castel di Guido (Rome) differs significantly in its overall morphology from that of a modern human. Furthermore, they argue that the "almost total absence of muscular impressions in the body's ventral surface suggests a reduced capacity for elevating this hyoid bone and modulating the length of the vocal tract in *Homo erectus*" (Capasso, Michetti, and D'Anastasio 2008:1007).

Similarly, there is little evidence for the use of symbols (Chase and Dibble 1987; d'Errico and Nowell 2000; d'Errico et al. 2003). Numbers of ochre "crayons" with use wear suggesting they were used on hard and soft surfaces have been recovered at Lower Paleolithic sites, but whether these colorants were used for symbolic purposes is unknown. They may well have been used to tan hides (Keeley 1978), as a mosquito repellent, for protection against the sun or against cold (Wadley 2001), for medicinal purposes (as an astringent, antiseptic, or deodorizer; references in Wadley 2001), for use in the extraction or processing of plants (Wadley 2001), for hafting (see Wadley 2010, in this issue), or for any number of as yet unknown/unimagined tasks. All other symbolic artifacts dating to this period are idiosyncratic, such as the Berekhat Ram artifact (d'Errico and Nowell 2000; Goren-Inbar 1986), and/or highly controversial (e.g., Rigaud et al. 2009).

Another angle on this question concerns whether the technologies of the Acheulian (see below) could have been learned and transmitted between individuals and across generations in an alinguistic environment, but this issue remains unresolved (see discussion in Nowell 2000). It is important to note that increased vocal communication does not necessarily mean language "as we know it" (Noble and Davidson 1996) and that nonvocal communication such as gestural communication could have increased in importance during this period.

### Tool Use

The earliest-known Acheulian industries date to 1.65 Ma. The Acheulian is characterized by the appearance of handaxes and the use of prepared core technologies, including the Levallois technique. *Homo erectus* transported raw material further than early *Homo* (and relative to the preceding Oldowan industries, the Acheulian is a more curated technology). As such, it represents a true technological innovation that coincides roughly with the emergence of *H. erectus*. After this initial surge in innovation, however, there is little evidence of progressive technological change or of a directional trend—it is as Glynn Isaac once said, “variable sameness” (see Clark, Cormack, and Chin 2001:612). Thus, in contrast to the life-history data, the associated Acheulian industries are often described as more or less stagnant over 1 million years and thousands of kilometers and across varied environmental settings (Nowell and White 2010). However, it is clear that there is a great deal more geographic diversity than is normally recognized within the Acheulian at site-level (Nowell and White 2010; Roe 1968), regional (e.g., Mussi 1995; Roe 1968; Vishnyatsky 1999; White 2000), and continent-level scales (e.g., Movius 1948; Petraglia and Korrisettar 1998; White 2000, 2006; Wynn and Tierson 1990). In fact, “while most Acheulian sites seem to show a modal tendency in handaxe morphology, variation is actually quite substantial, with the richer sites showing examples of practically every conceivable permutation in tool form” (Nowell and White 2010:72).

The difficulty in discerning any diachronic patterning at any scale within the Acheulian may at least in part be the result of low-resolution signatures; the patchy, palimpsest nature of the data; and poor chronological control of Acheulian sites (Nowell and White 2010; see also Nowell and Chang 2009). At the same time, there is an underlying reality to the perceived lack of directional change. This may be as Mark White and I (Nowell and White 2010) have argued elsewhere, on the basis of the work of Shennan (2001) that encounter rates between *H. erectus* groups were so low that it was less probable that true innovation would occur and spread. It is also likely that the initial pulse of technological “innovations” that characterize the early Acheulian were enough to satisfy the needs of a post-Oldowan lifeway until the next major shift in hominin life history (Nowell and White 2010). We argue that “changes in *H. erectus* life histories such as the introduction of a childhood phase, possibly greater levels of caregiving by old and skilled individuals, and changes in mobility and terrestriality facilitated the Acheulian and helped sustain a successful adaptation and certain level of fitness, but there was no pressure (or selection) for change exerted on the stone tools” (Nowell and White 2010:73). The flexibility of the Acheulian contrasts with tools used by nonhuman primates that are more task specific, and this versatility may have been key to exploiting a range of foods and to facilitating the move into new habitats.

Finally, the work of Haidle (2010, in this issue) is relevant

to the discussion of *H. erectus* tool use. She argues that when an individual animal of a species needs to use a tool to solve a problem, “at least in the short term, thinking must depart from the immediate problem and shift to abstract conceptualizations of potential solutions, which results in sequences of physical actions with objects appropriate to achieve a solution in the near future” (S153). She describes this as the *distance* (number of steps) from a problem to its solution. In nonhuman primates, for instance, chimpanzees using a termiting stick to “fish for termites,” the distance can be fairly small. She identifies nine steps that she divides into six phases. For Oldowan hominins (i.e., early *Homo* and possibly *Australopithecus garhi* and/or members of the genus *Paranthropus*), the situation is more complex. The use of an Oldowan stone tool to cut meat requires 13 steps divided into seven phases, including raw-material procurement, and the modification of more than one tool. She argues that the Acheulian fire-hardened wooden spears from the German site of Schöningen (Thieme 1997), dating to 400,000 BP, are a significant turning point because of the complexity of the behaviors involved. Hominins would have had to procure the raw material, transport a variety of elements, and manufacture a number of tools in order to make these spears, all while inhibiting distractions or at least being able to return to the problem at hand after being distracted. This entire process probably took several days. Thus, the distance between a problem (i.e., the need to kill an animal in order to satisfy hunger) and its solution increased exponentially (Haidle 2010). By this time period in Germany, the Acheulian is probably associated with *Homo heidelbergensis*, but the complexity of the prepared core technologies and of tools such as handaxes that characterize the early to middle Acheulian strongly suggest that the tool-using behavior of *H. erectus* was significantly more complex than that employed by previous hominin species.

### WM and the Speed of Life

In sum, there are more than 20 significant alterations in hominin life history that coincide with the emergence and development of *Homo erectus*. Antón’s (2003:156) phrase “a complex web of costs and benefits [that] worked together to allow the expansion of the brain as well as the body at the origin of *Homo erectus*” elegantly captures the interrelatedness of all of these factors and is a metaphor of how a change in one of these variables would have reverberations for the rest.

Diverse lines of evidence—some directly based on the fossil evidence and others inferred from the fossil evidence—strongly suggest that *H. erectus* populations experienced a slowed pace of ontological development relative to earlier *Homo* and nonhuman primates. On the basis of these data, it is reasonable to conclude that the hominin life-history stage of childhood was either present for the first time or significantly expanded in *H. erectus* populations. They probably experienced a (limited) adolescence as well. There are two important ramifications of these inferences. First, the hominin

pattern of “living fast” (e.g., “stacking” dependent offspring; see Robson and Wood 2008) within an overall pattern of “living slow” had begun to develop, greatly affecting the overall fecundity of the species. Second, the development of childhood and adolescent stages probably led to initial development of enhanced WM away from ape-grade abilities. During these additional years of growth and development, there would have been increased time for the development and maturation of the dorsolateral prefrontal cortex—for the pruning of irrelevant behaviors and the strengthening of others through the development of memory (and the ability to draw on past experiences), inhibition, and attention. At the same time, these new life-history stages would have allowed for increased interaction with peers through play. Play is the behavioral correlate of these cortical changes—it is during play that certain behaviors are reinforced and others are suppressed. This recursive relationship between hominin behavior and the maturation of the brain is reflected in the ability of *H. erectus* to be ground sleepers, to share meat and other food, to engage in persistence hunting, and to make cognitively more complex stone tools. These behaviors are possible only in the context of and in relation to many other changes taking place at this time, including the transition to obligate bipedality, the expansion of day and home ranges, changing body size and energetic requirements, and concomitant dietary shifts and related subsistence strategies.

In the same way that the evolution of bipedal walking is a result of dramatic anatomical, behavioral, and environmental changes, so, too, is the evolution of the hominin brain. Selection for a larger brain and enhanced WM among other cognitive abilities makes sense only in the context of all of the other life-history changes described in this paper. Life-history approaches are becoming more common in paleoanthropology as a means of breathing life into the stones and bones we study. As methodologies become more robust, life-history data will continue to contribute in a meaningful way to our understanding of the evolution of the hominin brain generally and to the development of enhanced WM more specifically.

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# Coevolution of Composite-Tool Technology, Constructive Memory, and Language

Implications for the Evolution of Modern Human Behavior

by Stanley H. Ambrose

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The evolution of modern human behavior was undoubtedly accompanied by neurological changes that enhanced capacities for innovation in technology, language, and social organization associated with working memory. Constructive memory integrates components of working memory in the medial prefrontal cortex to imagine alternative futures. Enhanced mental time travel permits long-range strategic planning. Within this broadly conceived area of cognitive neuropsychology, I will focus on two stages of the evolution of cognitive faculties for planning. The first involves executing complex sequences of actions involving manufacture of multicomponent artifacts; the second involves enhanced planning through information sharing, which required the establishment of extended regional social interaction networks based on trust and cooperation. Both stages were probably accompanied by important innovations in grammatical speech.

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## Introduction

Planning is considered to be a uniquely human form of memory for mental time travel to the future, and its emergence during the course of human evolution may have been a crucial factor in our current success (Suddendorf and Corballis 2007). Lewis Binford (1989) established the case for the role of planning in understanding innovations in technology and social systems accompanying the transition to modern human behavior. He stated that

focusing on the behavioral consequences of planning and on the organization of early hominid use of tools may be among the most productive avenues of research on the transition between the archaeological remains deposited before and after the appearance of *Homo sapiens sapiens*. (Binford 1989:19)

Binford's characterization of archaic, nonmodern human behavior as relatively unplanned is developed in a series of publications in which he argues that European Middle Paleolithic (MP) and African Middle Stone Age (MSA) humans wandered relatively randomly within restricted territories and reacted expediently to resource encounters and procurement opportunities such as scavenging animal carcasses and collecting raw materials for artifact manufacture (Binford 1984,

1985, 1989). Integrated analysis of Mousterian settlement distributions and lithic and faunal procurement patterns in coastal Italy documented by Kuhn (1992) provide empirical evidence for Binford's reconstruction of Neanderthal behavior. Neanderthal skeletal morphology, injuries, and pathologies evince a peripatetic, strenuous, prolonged daily travel routine and high levels of interpersonal violence (Berger and Trinkaus 1995; Trinkaus 1995). This is consistent with Binford's vision of opportunistic, unplanned resource exploitation. Widespread evidence for Neanderthal cannibalism (Defleur et al. 1999) and predominantly local lithic resource exploitation (Féblot-Augustins 1997; Kuhn 1992), suggests that Neanderthals lived in closed, defended territories and had minimal interactions with neighboring groups.

Similar evidence for cannibalism (White 1987) and limited lithic raw-material transport distances in southern African MSA sites (Ambrose 2006; Ambrose and Lorenz 1990) indicates that anatomically modern Africans were in some respects behaviorally archaic and similar to Neanderthals. Faunal resource exploitation patterns in South African coastal sites provides additional support for limited capacities to schedule land use to take strategic advantage of seasonal variation in resource availability (Klein 1989; Klein et al. 2004). In essence, these studies seem to show that behaviorally archaic hominids *reacted* to their environments. They appear to have traversed a large proportion of their apparently small home ranges during daily travel. Therefore, long-range planning of land use would not be essential.

The archaeological record of the last ice age, after 70 thou-

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**Stanley H. Ambrose** is Professor of Anthropology in the Department of Anthropology, University of Illinois (Urbana, Illinois 61801, U.S.A. [ambrose@illinois.edu]).

sand years (ka), marks the first appearance of planned use of larger home ranges. Klein's faunal evidence from southern Africa and Kuhn's settlement and lithic and faunal procurement evidence in Italy indicate that modern humans strategically planned and scheduled land use in what Binford (1984, 1989) calls "culturally constructed" environments. They had seasonally scheduled and intense use of sites rather than low levels of unplanned use throughout the year.

How did modern humans optimize scheduling of land use? Perhaps they developed enhanced long-term memories and understanding of seasonal environmental cues. However, most migratory species can schedule resource use and movement based on instinct, perhaps stimulated by environmental cues, rather than on memory and social learning. Intra- and interannual variability in resource availability may obviate the benefits of instinctive and/or memorized scheduling, especially in the variable environments of the last ice age. The culturally constructed environment concept suggests that social factors were involved in planning. Gamble (1993) characterized modern humans as living in "extended social landscapes" defined by interaction networks that united dispersed local groups. The niche construction concept (Odling-Smee, Laland, and Feldman 2003; Sterelny 2007) can be extended to capture the essence of Binford's idea of a culturally constructed environment as a defining feature of modern human behavior. Although niche construction theory focuses mainly on physical modifications to the environment (e.g., beaver dams), for the purposes of my thesis, the culturally constructed niche can be defined as the use of information obtained through social interaction (rather than memory) that permits structured, strategically planned, and anticipated use of the landscape and its resources. I propose that advanced planning and exploitation of culturally constructed niches became possible when information became widely shared through extended social information exchange networks that were established at the beginning of the last ice age (Ambrose 2002).

Long distances of transport of lithic and other raw materials in the Upper Paleolithic of western and central Europe and the late MSA of eastern and southern Africa (Ambrose 2002; Ambrose and Lorenz 1990; Féblot-Augustins 1997; Merrick, Brown, and Nash 1994) provide archaeological evidence support for the great extent (>300 km) and high intensity of modern human interaction networks during the last ice age. Social strategies invented by anatomically modern humans in Africa to establish and maintain these "culturally constructed" social landscapes may have been the last significant stage in the evolution of modern human behavior, cognition, and language.

The frontal lobe is implicated in our recent advances toward modern behavior because it is the seat of "executive functions" such as impulse inhibition, delayed gratification, task switching, coordination of activities, goal setting, costs and benefits evaluation, and planning. I will explore the archaeological evidence for the coevolution of technology, planning, and

language and its potential neurological correlates. However, a discussion of the definitions of working memory (WM) and related concepts seems appropriate before exploring this evidence.

## WM, Prospective Memory, and Constructive Memory

The concept of WM adopted by Coolidge and Wynn (2005; Wynn and Coolidge 2007) encompasses some of the frontal lobe executive functions noted above, particularly planning, but planning is not part of the definition of the concept of WM as used by many neuropsychologists, including its primary developer (Baddeley 2007). The following definitions, which emphasize the "here and now" of WM, seem to be intuitively implied by the term.

A cognitive system that provides temporary storage and manipulation of information that is necessary for a variety of complex cognitive tasks. (Medin, Ross, and Markman 2005:144)

*Working memory* (WM) is the term that cognitive psychologists use to describe the ability to simultaneously maintain and process goal-relevant information. . . . It is memory at work. (Conway et al. 2007:3)

The essence of WM is the capacity an individual has to hold and manipulate information in active attention. (Wynn and Coolidge 2007:79)

The broadly defined concept of WM used by Coolidge and Wynn (2005; Wynn and Coolidge 2007) includes short-term visual and phonological storage (the visuospatial sketch pad); attentiveness; and retrospective, episodic (autobiographical), semantic, declarative, and procedural (motor skills and habits) memory, as well as higher executive functions such as intentionality, monitoring of progress, and general intelligence. Some have argued that while WM capacity is often highly correlated with executive functions—including cognitive abilities such as general, fluid, crystallized, and other "intelligences"—they are clinically, experimentally, and statistically dissociable from them, and their conceptual boundaries should not be blurred (Blair 2006; Heitz et al. 2006).

By emphasizing planning, Coolidge and Wynn (2005) include in their thesis for the emergence of modern thinking cognitive features that are becoming conceptually differentiated in two related emerging fields of cognitive psychology. The first is prospective memory, which is defined as the encoding, storage, and delayed retrieval of intended actions (Graf and Uttl 2001; McDaniel and Einstein 2007). The second is planning and imagining the future, which falls within the conceptual domain of the even newer field of constructive memory (Schacter and Addis 2007). Prospective memory for delayed tasks and constructive memory for imagined futures both feed into the here and now of WM to varying degrees. However, subsuming them within conventional WM bounds



may disguise their conceptual distinctiveness. Conceptual distinction may also help us formulate questions that may help us understand the neurological basis for these different kinds of memory capacities.

The prefrontal region can be subdivided into several structurally and functionally different subareas that may be allocated to different kinds of memory (Addis, Wong, and Schacter 2007; Christoff and Gabrieli 2000; Koechlin and Hyafil 2007; Koechlin et al. 2000; Kringelbach and Rolls 2004; Szpunar, Watson, and McDermott 2007). Therefore, subsuming them all within the inclusive monolithic concept of WM may impede understanding of the specific neurological components that may have made one of the largest contributions to our modern human cognitive capacities. However, at the outset it is important to note that the prefrontal cortex has more extensive connections to other lobes of the brain and more extensive connections to the subcortical structures than any other cortical region of the brain (e.g., Gazzaniga 2009).

I will unpack this bulky suitcase of WM and shift the focus of inquiry to the kind of memory involving planning and coordination faculties of the frontopolar prefrontal cortex (FPPC; Brodman's area 10) and adjacent areas of the frontal lobe (Burgess et al. 2008; Christoff and Gabrieli 2000; Koechlin et al. 1999, 2000). The FPPC is proportionately larger in humans than in apes and is considered to be one of the most recently evolved areas of the human brain (Burgess, Gilbert, and Dumontheil 2007; Holloway 2002; Semendeferi et al. 2001; however, see Bruner 2010, in this issue). Functional brain-imaging studies suggest that the inferior frontal region can be functionally subdivided. The posterior/lateral area is apparently dedicated to the scratch-pad functions that are the heart of WM. The anterior/medial area seems dedicated to complex task and subtask execution related to the near-future goals of prospective memory and the goals set by longer-term constructive memory. These hierarchical levels of memory form a cascade that links the anterior/medial future memory and planning faculties with the posterior/lateral frontal lobe seat of WM *sensu stricto* (Christoff and Gabrieli 2000; Koechlin et al. 2000).

The WM concept described above implies a focus on immediate task completion. Prospective memory seems to imply longer-term goals. However, prospective memory theory and research also have a pragmatic and narrow focus on near-term goals such as daily activities, resumption of interrupted tasks, and persistence in completion of tasks. The cover of the book titled *Prospective Memory* (McDaniel and Einstein 2007) graphically portrays this faculty in a photograph of a daily to-do list on Post-it notes.

Prospective memory and WM as currently operationalized may suffice to capture the timescale of chimpanzee short-distance transport of objects for immediate tool-using activities. One could argue that it accounts for some aspects of the structure of the archaeological record of Neanderthals in western Eurasia and early anatomically modern humans in Africa. However, modern human planning depth implies

much more than the task-specific here and now of WM and the daily planner of prospective memory. This is the conceptual domain of constructive memory.

We remember the past, but we have the capacity to construct complex and ramifying imaginary futures and alternative scenarios that are crucial to our adaptive success. Modern humans are well aware of seasonal changes in their environment, and they strategically plan their movements and activities to anticipate such changes, for example, positioning camps to encounter migratory herds or fish runs, to harvest fruits and nuts when they ripen, and to maintain regular access to freshwater in the dry season. We plant, harvest, and store crops and construct irrigation systems, dams, furniture, factories, and cities.

The gulf between our closest living relatives and humans in capacities for imagining the future is apparently immense (Suddendorf and Corballis 2007). Primates may have the capacity for using environmental cues such as the ripening of a fruiting tree species to move via direct routes to remembered locations of other trees of that species that have ripened at the same time (Garber 2000). Perhaps they can remember the rich returns from yesterday and travel to the correct locations efficiently. In an experimental setting, a few precocious captive apes can retain a functional tool for use up to 14 hours later (Mulcahy and Call 2006). Whether primates can anticipate such opportunities and position themselves accordingly before they sense such proximate cues remains to be demonstrated. If we could ask a wild chimpanzee what it plans to do tomorrow, next week, or next month, what would it say?

As noted above, Coolidge and Wynn (2005; Wynn and Coolidge 2007, 2008) have expanded the WM concept to encompass long-range-planning capacities. They propose that constructed features such as walls, traps, and other planned facilities and activities—especially those that imply long-delayed returns, such as agricultural crops—are the archaeologically detectable evidence for planning. However, experimental research and theory (Baddeley 2007) on WM is currently sparse with regard to the cognitive neurology of planning. If the investigative realm of WM and prospective memory fails to include the modern human capacity for planning and imagining the distant future, then one must conclude that the thesis of enhanced WM is being planted in a sterile field and is thus unlikely to reap substantive insights into this important feature of the modern human mind. Perhaps Coolidge and Wynn should plant their thesis in the field that directly addresses issues of planning.

This distinctly human capacity for imagining the future is known as constructive memory (Schacter and Addis 2007). It activates many of the same prefrontal regions as those involved in remembering the past, particularly those associated with imagery for spatial scenes. Constructive memory experiments also activate a few distinctive areas that are associated with imagined body movements (Szpunar, Watson, and McDermott 2007) and with the episodic memory system (Addis, Wong, and Schacter 2007). Visualization of actions in

previously experienced settings is particularly interesting from the perspective of the hypothesized fundamental role of strategic land use planning and scheduling for the evolution of modern human behavior.

Constructive memory seems like an oxymoron because it implies remembering futures that have not yet happened. However, imagining the future draws on retrospective, episodic, and autobiographical memory (personal events and experiences); declarative memory (general knowledge); and procedural memory (habitual and learned sequences of action) to construct novel scenarios. If these imaginary futures become actionable plans, then they may set objectives for goal-oriented behaviors that are eventually transferred into the to-do list of prospective memory and finally into WM when the task is being executed. This cascade from constructing futures to planning to perform activities and then to acting on these plans is considered uniquely human (Suddendorf and Corballis 2007).

Evolving innovative enhanced capacities to assemble components of existing stores of knowledge, procedures, skills, and episodic memories to construct new imaginary futures may be related to and may have coevolved with our capacities to assemble simple materials into composite artifacts and to assemble simple sounds into syntactically meaningful speech. Humans also strategically construct complex and extensive webs of reciprocal cooperative social relationships (cultural niche construction and extended social landscapes) that help them to achieve long-range goals such as mitigating resource insecurity (Wiessner 1982, 1986). I will return to these fundamental points about the potential homologies of assemblies of artifacts, syntactic speech, and social relationships.

The evolution of human cooperation, trust, and reciprocity is being theorized, modeled, and investigated by social and behavioral scientists in many disciplines, including anthropology, economics, ecology, ethology, political science, endocrinology, and neurology (Dawes et al. 2007; Fehr and Henrich 2003; Hammerstein 2003; Kosfeld et al. 2005; Krueger, Grafman, and McCabe 2008; Krueger et al. 2007; McCabe et al. 2001; Nowak and Sigmund 2005; Richerson, Boyd, and Henrich 2003; Riolo, Cohen, and Axelrod 2001; Smith 2003; Zak 2008). Some of this research shows that the anterior frontal lobe is also activated in evaluating the intersubjective “theory of mind” (“I think I know what you think I am thinking”; Povinelli and Preuss 1995) potentials for cooperation and reciprocation in others and our decisions to engage in such relationships depending on the perceived probabilities of reciprocation (Krueger, Grafman, and McCabe 2008; Krueger et al. 2007; McCabe et al. 2001). Related research shows that certain hormones can influence trust, reciprocity, generosity, and social attachment (Donaldson and Young 2008; Dunbar 2010; Walum et al. 2008; Zak, Kurzban, and Matzner 2005; Zak, Stanton, and Ahmadi 2007; Zak et al. 2005), all of which are essential for establishing systems of cooperation.

## Archaeological Evidence for Enhanced Planning

Two important behavioral innovations that appear in the archaeological record of the last 300,000 years—(1) composite-tool manufacture (Ambrose 2001) and (2) regional social exchange networks (Ambrose 2002)—may have coevolved with the anterior frontal lobe. These stages may be closely coordinated with parallel stages in the evolution of syntax and grammar in language, and the first stage may have coevolved with the neurological areas of the temporal lobe devoted to grammatical language and manual fine-motor control.

### *Stage 1: The Transition from Single Component to Composite Technologies*

The Lower Paleolithic and Early Stone Age (Oldowan and Acheulean) are *reductive* technologies that produce single-component handheld stone tools. Conversely, the MP and the MSA are characterized by *additive* multicomponent composite-tool technologies (Ambrose 2001). Making Oldowan flakes and core tools and Acheulean handaxes and other large cutting tools involves chipping (flaking) of large pieces of stone (cores) by repetitive hammering actions to knock off thin flakes with sharp and durable functional edges. The large cores from which these flakes are removed also have strong, sharp functional edges. Coarse motor control areas of the brain are predominantly active in this mode of manufacture (Stout and Chaminade 2007). Brain-imaging studies of unskilled novices engaged in direct percussion stone flake production show that

simple stone tool making is supported by a mosaic of primitive and derived parietofrontal perceptual-motor systems. . . . *No activation was observed in prefrontal executive cortices associated with strategic action planning or in inferior parietal cortex thought to play a role in the representation of everyday tool use skills.* (Stout and Chaminade 2007:1091; italics added).

However, a later study using expert toolmakers showed

increased demands for effective visuomotor coordination and hierarchical action organization in more advanced tool-making. This includes an increased activation of ventral premotor and inferior parietal elements of the parietofrontal praxis circuits in both the hemispheres and of the right hemisphere homologue of Broca’s area. (Stout et al. 2008: 1939)

Although substantial bilateral activity occurred for some regions of the brain, increased activity was not seen in the left hemisphere in Broca’s area, which is one of the primary centers for the production of syntactic grammatical speech (Hagoort 2005; Lieberman 2002). They note that right-hemisphere activity is partly due to the important role of the left hand in correct positioning of the core that is being reduced (Stout et al. 2008:1945).

Large cutting tools are often considered the products of highly skilled individuals that envisioned preconceived shapes of artifacts. However, this assumption has been contested (Ambrose 2001; Davidson 2002). Moreover, although some of these tools are extremely symmetric and appear finely crafted, they remain single-component handheld artifacts that were shaped by reduction. Lower Paleolithic wooden artifacts, such as the famous 400,000-year-old spears from Schoeningen (Thieme 1997), are also considered finely crafted tools evincing advanced skill and cognition. However, like handaxes, they are single-component artifacts and are shaped solely by reduction using repetitive whittling and scraping actions. They are thus likely to use neurological pathways similar to those used for percussion-flaked stone tool manufacture.

A small number of component materials and manufacturing steps are involved in reductive technologies, for example, a core and a hammerstone or a flake and a piece of wood. If the time and distance between the materials necessary to complete Lower Paleolithic tool manufacturing tasks are small, there may be little need for prefrontal planning faculties. Lower Paleolithic hominins may have been experts in their fields, but they may have relied mainly on prospective memory and WM in tool manufacture and use. However, the fact that early hominins were habitually carriers of tools and weapons (Toth 1985) implies that they had at least general expectations that there would be opportunities for tool use, and thus they had a general capacity for planning. Lithic raw-material transport distances are significantly shorter in the Lower Paleolithic and Early Stone Age than in the MP and MSA (Féblot-Augustins 1999; Merrick, Brown, and Nash 1994). This may partly reflect smaller home range sizes and stronger territorial boundary defense, but it may also simply represent less curation of artifacts. In other words, artifacts that have shorter use lives are more likely to be abandoned closer to their geological sources. The curation hypothesis may be correct for the relatively expedient small stone tools of the Oldowan (Toth 1985), but it does not seem compelling for the Acheulean, especially considering the resharpening and rejuvenation potentials of large cutting tools such as handaxes (Hayden 1987). In other words, compared with simple Oldowan flakes and cores, handaxes and other large cutting tools were probably carried longer and edges were maintained and used more before being discarded. The short transport distances of curated Acheulean artifacts thus imply that early hominins had small home ranges and little interaction with neighboring territorial groups.

Composite-tool manufacture—involving the mounting (hafting) of stone artifacts in handles with gums, cords, sinews, and/or other binding materials—appears at the transition from the Acheulean to the MP and the MSA. The Sangoan industrial complex of tropical sub-Saharan Africa spans the transition from the Acheulean to the MSA, around 300 ka (McBrearty and Tryon 2005). Large, heavy-duty stone tools such as core axes, picks, and lances characterize this industrial complex. Microwear evidence from the Sangoan core axe

quarry site on Sai Island, Sudan, shows that worn core axes that were made of raw materials that do not occur at the quarry bear hafting and dehafting wear and damage traces (Rots and Van Peer 2006). Worn axes were apparently removed from their handles at the quarry and were replaced with new ones that were made at this quarry. Artifacts with mastic from a MP site in Syria (Boëda et al. 1996) provide evidence that MP flake-based tools such as points were hafted. Additional evidence for hafting in the MSA comes from Sibudu Cave, South Africa (Lombard 2005; also see Wadley 2010, in this issue).

Making a composite tool, for example, a stone-tipped spear or a hafted stone axe, requires collecting and preparing several kinds of components composed of different raw materials that may be obtained at different times and in different places (Stout 2002; Toth, Clark, and Ligabue 1992). The final assembly of the functional artifact may occur much later, and some materials may be kept in reserve for maintenance and repair of composite tools. Composite-tool manufacture in the MP and MSA thus marks an order-of-magnitude increase in technological complexity compared with the single-component tools of the Lower Paleolithic (Ambrose 2001; also see Haidle 2010, in this issue). In comparison with Lower Paleolithic and Early Stone Age humans, MP hominids must have had much more need for the constructive memory and planning faculties of the anterior frontal lobes.

Koechlin et al. (1999) provide support for the hypothesis that additive (composite-tool) technologies coevolved with neurological capacities of the FPPC for planning and complex task coordination. Using functional magnetic resonance imaging, Koechlin et al. (1999) showed that

bilateral regions in the FPPC alone are selectively activated when subjects have to keep in mind a main goal while performing concurrent (sub)goals. Neither keeping in mind a goal over time (working memory) nor successively allocating attentional resources between alternative goals (dual-task performance) could by themselves activate these regions. Our results indicate that the FPPC selectively mediates the human ability to hold in mind goals while exploring and processing secondary goals, a process generally required in planning and reasoning. (Koechlin et al. 1999: 148)

This study apparently shows that our capacity for completing complex constructive subtasks related to long-range goals draws on constructive memory faculties that reside in the anterior prefrontal cortex and that this area is not recruited for WM or for prospective memory. Imaging studies performed by Johnson-Frey, Newman-Norlund, and Grafton (2005) provide specific evidence for the role of this area in planning of tool use. They observed several areas of the left hemisphere that were consistently recruited during tool use or while imagining tool use. They expressed surprise that the dorsolateral prefrontal cortex

is the only region in the left hemisphere that was exclusively active . . . during action planning and not execution. . . . This area may be involved in the access and/or maintenance of information in semantic working memory. (Johnson-Frey, Newman-Norlund, and Grafton 2005:692)

Koechlin et al.'s (1999, 2000) results suggest that they should not be surprised that planning tool use could stimulate such prefrontal activity. These studies (reviewed by Johnson-Frey [2004]) provide a strong foundation for understanding the neurological basis for the relationship between WM, prospective memory, constructive memory, and planning of tool use.

The homologous neurological pathways for syntactic speech and manual artifact assembly in Broca's area (Binofski and Buccino 2004) suggest that composite-artifact manufacture and grammatical language also coevolved (Ambrose 2001; Greenfield 1991). Lower Paleolithic stone tool manufacture by reduction appears to have contributed little to stimulation of neurological areas homologous with those for grammatical language and manual hierarchical assembly (Stout et al. 2008). If composite-tool technologies date as far back as 300,000 years, then Neanderthals could speak grammatically (Ambrose 2001). Brain-imaging studies involving tool assembly are needed to evaluate Greenfield's (1991) hypothesis of homology of grammatical language and composite-tool manufacture.

### *Stage 2: Assembly of Social Networks*

Stage 2 is marked by the transition from restricted (primate trooplike) to extended social landscapes (band networks or tribes) at the beginning of the last ice age, around 70 ka (Ambrose 2002). This transition is considered to represent the establishment of intensive regional reciprocal information sharing, cooperation, and materials exchange systems (Ambrose and Lorenz 1990; Gamble 1993; McBrearty and Brooks 2000).

Archaeological evidence for this troop-to-tribe transition comprises an abrupt increase in the amounts of stone artifacts that are made on exotic lithic raw materials that come from distances greater than the maximum diameter of pedestrian hunter-gatherer home ranges (Ambrose 2002, 2006; Ambrose and Lorenz 1990; Merrick, Brown, and Nash 1994), which is approximately 40–45 km (Gamble 1993; Gould 1978; Gould and Saggars 1985; Whallon 2005). The exotic stone hypothesis has been justifiably contested for the Howiesons Poort lithic industry in the MSA of southern Africa (Minichillo 2006) because geochemical data on the geographic sources of the artifacts is absent (Ambrose 2006). However, in East Africa, where obsidian (volcanic glass) artifact sources are easily located and chemically fingerprinted, there is incontrovertible evidence for an order-of-magnitude increase in the abundance of long-distance transport of obsidian near the end of the

MSA (Ambrose 2002, forthcoming; Merrick, Brown, and Nash 1994).

It is notable that this transition within the MSA occurred at the beginning of the last ice age, when the genetic structure of modern human populations suggests a catastrophic population crash around 74 ka (Ambrose 1998, 2003). This population bottleneck is followed by a population expansion around 60–70 ka among all African populations and then by expansions of the ancestors of southern Australasians around 60 ka and northern Eurasians around 50 ka (Forster 2004; Jorde, Bamshad, and Rogers 1998). The period from approximately 74 to 72 ka witnessed a catastrophic volcanic winter lasting 6 years that may have initiated a severe instant ice age lasting 1,800 years, known as Dansgaard-Oeschger stadial 20 (Williams et al. 2009; Zielinski et al. 1996). Two millennia of relatively warm (interstadial) climate separated this severe event from the early last glacial maximum (known as marine oxygen isotope stage 4), which lasted from 71 to 60 ka (NGRIP 2004; Zielinski et al. 1996). Stage 4 was consistently colder and lasted longer than the late last glacial maximum (stage 2), 26–14 ka. The prolonged cold, droughts, and famines from 74 to 60 ka are probably responsible for the severe population bottleneck recorded in Africa at this time.

Severe environmental disasters in marginal environments such as those that probably predominated during the early last ice age are considered a strong selective force for the evolution of cooperation within and especially between groups (Fehr and Henrich 2003; Richerson, Boyd, and Henrich 2003). Modern hunter-gatherers in extreme environments, including Western Australian Desert Aborigines (Gould 1978) and Kalahari Desert foragers in southern Africa (Wiessner 1982, 1983, 1986), provide appropriate models for the role of social cooperation and information exchange in adaptations to severe environments of the early last ice age. Eskimos and Great Basin Shoshone Indians provide additional examples (Fehr and Henrich 2003; Richerson, Boyd, and Henrich 2003). In such environments, where variance in resource availability is high and environmental disasters occur at irregular intervals, people actively seek reciprocal exchange relationships with individuals in distant, ecologically complementary environments. Frequent visits and gift exchanges function to maintain rights of reciprocal access to foraging in their partners' territories. These visits are also occasions for gathering information about the state of the environment. Shared information is crucial for formulating plans for resource exploitation and for averting starvation when resources fail within a home range. In stable, productive environments, where resources are abundant and predictable, these intensive long-distance exchange systems are poorly developed or absent, even among Kalahari hunter-gatherers (Wiessner 1983), but they are a characteristic feature of foragers in severe environments (Dyson-Hudson and Smith 1978; Gould 1978).

The organization of stone tool technology may have changed substantially when these information-sharing net-

works were established in Africa. Theories of technological organization have provided great insights into patterns and strategies of artifact design and use in different environmental contexts (Kelly 1988; Kuhn 1992). Mobile foragers would be excessively burdened if they had to carry the right tool for every possible task they encountered. If the kinds of opportunities for tool use were hard to predict, then a tool kit comprising generalized, durable, and transformable tools would be useful for a wide range of tasks. Acheulean and earlier MSA and MP artifacts were often made on large, relatively thick flakes that were durable and maintainable and could be transformed expediently. These jack-of-all-trades artifacts are often difficult to classify in standard typological systems because they were apparently opportunistically modified for a wide range of activities.

When exotic fine-grained raw materials became abundant, they were often made into thin, sharp-edged, blade-based artifacts. These kinds of artifacts are more effective because they are sharper, but they are also more fragile because they are so thin. Experiments show that in comparison to broader, thick flakes, blades have limited potentials for resharpening (Eren, Greenspan, and Sampson 2008). Blades are often too narrow and thin to be transformed expediently for use in unanticipated tasks. They are designed for a limited range of tasks, and because of their fragility, replacements should be carried for repair. These kinds of tools—the right tools for the job—can predominate when activities can be anticipated and planned in advance (Ambrose 2002; Kuhn 1992). The basis for such planning would have been a larger pool of information about the environment obtained by reciprocal information sharing and cooperation.

The archaeological evidence for this technological transformation in southern Africa is first found in the Howiesons Poort lithic industry at 60–70 ka (Wadley 2008; Wurz 2002) and in the Mumba industry in East Africa at about the same time (Ambrose 2002, 2006; Mehlman 1989, 1991). The most diagnostic artifacts are thin blades trimmed into geometric shapes such as crescents and trapezes, with one long, sharp, unmodified edge and blunting (backing) on the opposite edge. They contain clear traces of components of adhesives for hafting (Lombard 2007). These backed segments are the functional equivalent of disposable razors. They are often made on fine-grained exotic raw materials (Wurz 2002). In East Africa, small, casually made thin points that resemble arrowheads appear alongside the microlithic segments in sites dating to older than 50,000 ka (Ambrose 1998, 2002; Mehlman 1989, 1991). These small points have clearly not been resharpened many times and thus have short use lives, like the backed-blade segments. On the basis of an analysis of prehistoric technological change in Nevada, Kelly (1988) proposed that a “shift to small, frequently unifacial, nonresharpenable points may indicate a shift to target-specific hunting strategies” (717). African foragers may have adopted similar target-specific strategies at the beginning of the last ice age. The

shift to specific targets may have been feasible only with enhanced information-sharing networks (Ambrose 2002).

Enhanced coordination of the FPPC and Broca’s area may have greatly facilitated strategic planning of land use and constructing enduring intergroup cooperation and information exchange networks. Assembling and maintaining strategic social relationships over a lifetime would involve constructive, prospective, and WM faculties. Although the catastrophic onset of the last ice age may have been the catalyst for enhanced cooperation, and cooperation was probably necessary for survival during this prolonged era of risk and uncertainty, climate change remains an incomplete explanation for its cause. Hominids had survived ice ages of similar duration and severity at least nine times in the past 1 million years. Neanderthals also survived the same climatic regimes, including the most catastrophic changes at the beginning of the last ice age, and did so in what was probably more challenging, higher-latitude cold environments, but they apparently did not significantly expand social cooperation networks beyond local groups.

If composite-tool manufacture reflects a substantial advance in planning and hierarchical assembly of artifacts, and equivalent capacities for composite-tool making and thus grammatical language were shared by Neanderthals and modern humans, then what made anatomically modern African humans different? One difference appears to be enhanced capacity for symbolism in Africa and the Levant before 70 ka, as evinced by examples of red ochre with abstract incisions, shell beads, and pendants (D’Errico et al. 2005; Henshilwood et al. 2002; Hovers et al. 2003; Mackay and Welz 2008), as well other aspects of technology, organization, subsistence, and symbolic behavior (McBrearty and Brooks 2000). Despite the far greater intensity of research on Neanderthal sites, the evidence for such symbolic behaviors before 40 ka in regions where Neanderthals were not in potential contact with anatomically modern humans is remarkably scarce (Zilhão 2007) and is securely evinced only by systematic burial of the dead. Symbolism and sociality are not necessarily synonymous (ask any antisocial or reclusive creative genius), so one cannot infer that the earliest evidence for symbolic behavior is necessarily associated with extended cooperative social formations.

Ornaments may have been used to symbolize ethnic identity and affiliation among dispersed populations (Kuhn et al. 2001) and may have thus acted as enhancers of cooperation (Ambrose 2002). Ethnographic evidence for the role of systematic delayed reciprocal gift giving shows that beadwork and other nonfunctional artifacts play an important role in maintaining and signifying long-distance cooperation networks (Wiessner 1983, 1986, 1994). Agent-based simulations have independently shown that such tag-based systems of identification can reinforce cooperation and reciprocity (Riolo, Cohen, and Axelrod 2001).

Was the invention of a tag-based system of signaling reciprocity sufficient to propel modern humans to more complex cooperative systems in Africa, or were genetically based

changes necessary? Wynn and Coolidge (2004; Coolidge and Wynn 2005) propose a genetic mutation for enhanced phonological loop capacity for storing larger numbers of words and concepts in WM, and they suggest that this enhancement also facilitated more sophisticated language and speech. Beaman (2007) has thoroughly critiqued this hypothesis and considers the evidence for an enhanced phonological loop to be weak. However, Martín-Loeches (2006) finds the hypothesis persuasive and argues that several components of WM may have been enhanced either by increases in neuron number or by allocation of energy to activating more neurons simultaneously, and he suggests three candidate genes that may be responsible for enhancements. Wynn and Coolidge (2007) also proposed that a single additive genetic change could work in synergy with preexisting genes to permit enhanced WM. They suggest that a new *Microcephalin* gene variant may be involved, but its estimated date of appearance is only 37 ka, which is too late for it to be fixed in populations on different continents that diverged genetically no later than 50 ka. Klein (2003) proposed that a mutation in the *FOXP2* gene around 50 ka was responsible for modern grammatical language capacities. However, Neanderthals share an identical *FOXP2* sequence (Krause et al. 2007), so this language gene hypothesis for the late expression of modern behavior can be discounted. Indeed, any model of the evolution of modern human behavior that involves novel genetic changes after 50 ka is untenable if the genetic divergence of living human populations, all of which have modern symbolic capabilities, is in the range of  $195 \pm 32$  ka (Gonder et al. 2007).

Richerson, Boyd, and Henrich (2003) have proposed a “tribal social instinct hypothesis” for the evolution of human cooperation in response to Pleistocene climatic variability and stress. The genetic loci for symbolism and social instincts remain unspecified, and one could argue that identifying such loci is unnecessary. However, the assumption that there is a genetic component for symbolism or tribal instinct becomes an article of faith if the genetics and neurobiology underlying evolved cognitive adaptations are assumed rather than demonstrated. Perhaps the behavioral innovation of composite-tool manufacture discussed above promoted selection for the genetic foundation of enhanced constructive and prospective memory and long-range planning. Although I have not specified genetic loci that may be responsible for these enhanced capacities, I have identified specific behaviors that would select for such enhancements, and neurological-imaging studies have identified some of the recently evolved areas of the frontal lobe that are activated in planning. It is unlikely that single mutations could be responsible for such capacities, but the imaging studies show us where to look for expression of novel genetic variants. If advances in sequencing of Neanderthal genes continue (Green et al. 2006; Krause et al. 2007; Noonan et al. 2006), it may be possible to test genetic mutation models of the origins of modern human behaviors.

Natural selection acts on preexisting variation. Gene-culture coevolution theory proposes that new cultural be-

haviors may select for previously rare genetic variants, for example, the gene variant (allele) that permits human adults to digest lactose (Laland 2004). Before the advent of dairying in agriculture, this allele was undoubtedly rare, but it has achieved high frequencies in the past 10,000 years in societies where milk is an important dietary staple. Perhaps the evolution of modern human cooperative behavior involved selection for previously rare genetic variants rather than new mutations that spread immediately because of their assumed adaptive advantages. Genetic variants facilitating cooperation may have existed long before they became prevalent because they may have become advantageous in a new social and natural environment only during the early last glacial era. I will now propose a more specific model for this important stage of the evolution of modern human behavior that involves natural selection for a simple change in gene frequencies for one or more preexisting neuroendocrine receptors combined with an innovation in language, both of which enhanced trust, cooperation, and reciprocity.

### The Language of Diplomacy, Flattery, Friendship, and Love

Grammatical innovations for indirect speech (Pinker, Nowak, and Lee 2008), which I prefer to call the language of diplomacy, may have facilitated the mutual trust required to maintain reciprocal cooperation. Direct forms of speech such as speaking in the imperative or the declarative present tense may have sufficed for communication and cooperation within a social group, especially if there was a highly structured dominance hierarchy. However, imperative commands, demands, and orders are unlikely to foster trust in intergroup relationships. Indeed, if the evidence for stimulation of dihydrotestosterone and aggression by unfair treatment is any guide (Rilling et al. 2008; Zak et al. 2005), distrust and resentment may result from imperative speech.

Passive grammatical constructions—for example, the third-person interrogative, abstract, and subjunctive constructions, such as posing hypothetical solutions (“What if *one* were to try to do something this way?”)—would be nonthreatening forms of speech that would permit individuals to make the choice to follow suggestions and to cooperate, thus preserving dignity and agency and engendering trust. There is a world of difference between ordering someone to join a risky hunt and saying “I heard that the wildebeest migration started early. If we moved to the game pass and worked together, we could get enough meat for both of our families for weeks. Would you like to join our camp?” Such a diplomatic voicing of a constructive memory scenario would be a good start on a long and mutually rewarding relationship and a strong foundation for extended social landscapes.

Perhaps language played a role in stimulating oxytocin and vasopressin production analogous to that played by touch and grooming. Among primates, grooming may increase oxytocin, vasopressin, and endorphin levels, thus reducing stress and

facilitating social bonding (Dunbar 2010). Conventional trust-game experiments show that massage significantly increased oxytocin if it was followed by an intentional act of trust and that generosity was positively correlated with increase in oxytocin (Morhenn et al. 2008). Dunbar (1993, 2003) proposed that social grooming, which occupies a substantial amount of time, was replaced by vocal grooming of several individuals simultaneously when hominid group sizes exceeded a threshold that required allocating more than 30% of the time budget to one-on-one grooming. If vocal grooming has the same effect as tactile stimulation, then the repertoire of the language of diplomacy and indirect speech may have also included the language of affirmation, compliments, friendship, and flattery. So prefacing the cooperative hunting offer above with “Your spear looks mighty fine, and I bet you can throw it pretty far” might prime the neuroendocrinological pump for reciprocity trust and cooperation. This language-of-love hypothesis should be easily testable in the lab by substituting vocal grooming for massage in the well-designed experiments of Morhenn et al. (2008).

I propose that Neanderthals may have been deficient in the neuroendocrine receptor variants that responded to the hormones that have been shown to correlate with trust, reciprocity, and cooperation, and they may have had an excess of receptor variants sensitive to aggression-stimulating dihydrotestosterone. Under the severe environmental stresses at the beginning of the last ice age, African modern humans that had higher frequencies of cooperation-facilitating hormone receptor variants may have had greater chances of survival. With an order-of-magnitude increase in the scale of social networks based on trust, cooperation, and reciprocity, humans could survive in much harsher unpredictable environments and explore new ones (Ambrose 1998, 2002, 2003). Linguistically and hormonally mediated social innovations may have facilitated the expansion of modern humans out of Africa.

## Discussion and Conclusions

The concept of WM used by Coolidge and Wynn (2005; Wynn and Coolidge 2007, 2008) has grown to encompass several domains of cognition that should probably be examined separately and be more narrowly defined in order to clearly trace the cognitive route from archaic to modern human behavior. The concept of WM should be restricted to the cognitive domains of “memory at work” (Conway et al. 2007). Prospective memory, which refers to the near-future tasks on the daily planner and to task switching (McDaniel and Einstein 2007), can be considered short-term-delayed WM. Long-range planning is the domain of the emerging field of constructive memory, which refers to imagining the future (Schacter and Addis 2007). Constructive memory generates plans by assembling personal past experiences (retrospective, episodic autobiographical memory), knowledge (declarative memory), and learned skills and actions (procedural mem-

ory). Thought experiments can be performed on alternative constructions of the future, and a final plan (and perhaps contingent plans) can be selected among the alternatives. When plans are selected, they can be transferred to prospective memory, and when enacted they enter the realm of WM.

I wholly agree with Coolidge and Wynn (2005; Wynn and Coolidge 2008) that long-range planning and delayed returns on activities are crucial components of modern human cognition and behavior. However, I propose that complex planning is evinced far earlier in the archaeological record in the form of composite-tool manufacture and that this capacity was shared with Neanderthals (Ambrose 2001).

The archaeological and bioarchaeological record of the transition to modern human behavior suggests that the most fundamental changes involved enhanced capacities for planned use of the landscape, resources, and social relationships. Lower Paleolithic stone tool manufacture appears to have contributed little to stimulation of prefrontal lobe planning faculties (Stout and Chaminade 2007). The first stage in the evolution of enhanced planning abilities probably involved constructing composite artifacts, which would have placed greater demands on integrating WM with prospective memory and, ultimately, constructive memory. These faculties reside in the anterior frontal lobe and Broca’s area. Lower Paleolithic stone tool manufacture by reduction appears to have contributed little to stimulation of neurological areas homologous with those for grammatical language and manual hierarchical assembly (Stout et al. 2008).

The second stage involved enhanced abilities to play social chess, in other words, to be able to gauge the intentions of others, to make decisions about whether cooperation will be rewarded with reciprocation, and to employ forms of speech that engender trust and reciprocity and perhaps increase generosity. The seat of this Machiavellian intelligence (Humphrey 1989) faculty for theory of the mind apparently resides in the same area of the prefrontal lobe as do our prospective and constructive memory faculties (Krueger, Grafman, and McCabe 2008; Krueger et al. 2007; McCabe et al. 2001). Social cooperation may have coevolved with further enhancements in abilities to plan and imagine alternative futures. Innovations in nonthreatening grammatical constructions of indirect speech (Pinker, Nowak, and Lee 2008), such as conditional, subjunctive, future, and third person, engender trust and cooperation. Such obtuse, hypothetical, future-tense forms of speech that characterize the language of diplomacy give voice to human constructive memory faculties. The language of compliments, flattery, and friendship may have substituted for social grooming to stimulate neurologically active hormones such as oxytocin and vasopressin to increase trust, generosity, reciprocity, and other affiliative behaviors while disarming the socially disruptive effects of dihydrotestosterone and cortisol. Comparison of Neanderthal and modern human genes for these neuroendocrine systems could help test this hypothesis.

Disastrous environmental degradation at the beginning of

the last ice age may have been the catalyst for forcing the expression of this capacity for cooperation at this crucial transition in the archaeological record of the evolution of modern human behavior. The troop-to-tribe transition may have been essential for the few survivors of this disaster. Neanderthals apparently had respectable working, prospective, and constructive memory capacities for making composite tools, but their skeletal biology and pathologies, as well as their poorly timed use of seasonally available resources, suggest that they were unable to realize their capacities for planning and land use. Evidence for cannibalism and the rarity of artifacts made on materials outside of their territorial boundaries suggest they lacked cooperative extraterritorial social networks. Did they become extinct because they were lousy social chess players? And what might be the cognitive prerequisites of successful chess players? Perhaps they lacked the language of diplomacy and the neuroendocrine receptors necessary for trust and reciprocity. In the risky environments of the last ice age, regional cooperation and reciprocation were probably better adaptive strategies than territorial defense and selfishness. Loving thy neighbors had greater long-term advantages than eating them.

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# Working-Memory Capacity and the Evolution of Modern Cognitive Potential

Implications from Animal and Early Human Tool Use

by Miriam Noël Haidle

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Tool use is the main database to track down behavioral developments in the archaeological record and thus human evolution. Working-memory capacity and modern cognitive potential, however, are no simple and obvious characters in tool behavior. Coded in cognigrams, which allow a direct comparison, animal and human tool use can be examined for specific aspects of the working-memory capacity. Detailed studies of tool behavior of wasps, sea otters, bottlenose dolphins, and chimpanzees are presented and compared with the manufacture and use of Oldowan tools and Lower Paleolithic spears. Although this shows a wide range of problem-solution distances, problem solving in animals seems to be restricted to problem complexes for which a solution can be found in spatial and temporal vicinity. In human evolution, the complexity of tool behavior increases regarding the number of active foci managed at a time in an action, the number and diversity of operational steps in a problem-solution complex, and the spatial and temporal frame in which solutions are sought. The results suggest a gradual development of the different aspects of a complex capacity instead of a late introduction of a closed phenomenon with only different facets.

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Modern human behavioral and cultural capacity is not an easy thing to study. The characterizations of the subject itself and its cognitive basis vary with the disciplinary and theoretical standpoints of the researchers. The explanation for the evolution of modern behavioral, cultural, and cognitive capacities and the methodological approaches to track its developmental steps follow the common disciplinary pathways and are constrained by the available data. The different perspectives become evident when archaeological and neuropsychological approaches are compared. Combining these approaches offers the perfect solution to overcome the limitations of both attempts. It remains to be seen how close they can come to each other and intertwine to create a synthetic model.

Archaeological definitions of modern human behavior focus generally on the presence or absence of certain material traits, such as blade technology, bone and antler industry, art, personal ornaments, and burials (for a compilation and critical assessment, see Belfer-Cohen and Hovers 2010; Davidson 2010, both in this issue; Henshilwood and Marean 2003).

These traits were originally thought to be exclusively associated with early modern humans in Europe. Symbolic thought, with its capacity for language and its conceptual extension of planning and foresight, has often been defined as an underlying, though not all-encompassing, cognitive concept. However, alternative interpretations exist. Mithen (1996) recognizes the development of cognitive fluidity among formerly separated mental modules—including general intelligence, social intelligence, natural history intelligence, technical intelligence, and language—as the main cognitive development toward modern human thought and as a prerequisite for symbolic thought. The basic paradigm of symbolic thought is regarded as both central to and partially causal of modern human behavior. The laundry list of material indicators is rarely questioned by archaeologists, whether they are supporters of the idea of a late cognitive big bang around 50,000 BC (Klein and Edgar 2002; Mellars 2005), an early development parallel to anatomical modernity in Africa and a subsequent coexpansion out of Africa (McBrearty and Brooks 2000), or parallel, gradual, cognitive cultural developments in several regions of the world independent of biological species (Conard 2007; d'Errico 2003). The concept may be diluted by additional cognitive facets and their markers, such as the settlement of islands and continents (Noble and Davidson 1996), the use of marine resources by seafaring, or the acceptance of indicators of probable preliminary stages, such as

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**Miriam Noël Haidle** is Coordinator of the Role of Culture in Early Expansions of Humans Research Center of the Heidelberg Academy of Sciences and Humanities at the Senckenberg Research Institute (Senckenberganlage 25, D-60325 Frankfurt am Main, Germany [miriam.haidle@uni-tuebingen.de]).

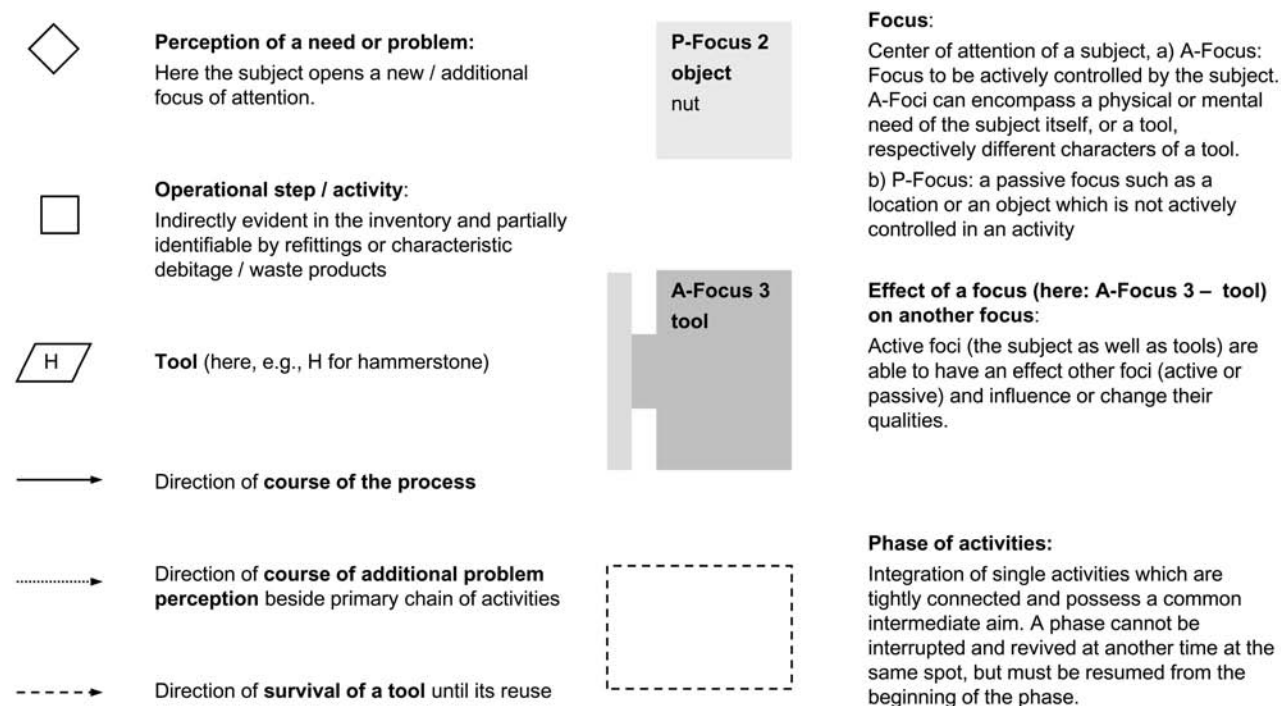


Figure 1. Signs and symbols used to code thought-and-activity processes in cogramms.

the use of mineral pigments (Marean et al. 2007). While a majority of archaeologists regard symbolism as a strictly present or absent trait, Rossano (2010, in this issue), for example, argues for progressive stages that can be found in the archaeological record.

A completely different approach, taken from a neuropsychologist's perspective, proposes that the evolution of the executive functions of the frontal lobes is a cognitive key element in the evolution of modern human behavior and culture (Coolidge and Wynn 2001). The executive functions are embedded in the broader theoretical framework of the concept of working memory (Baddeley 1993, 2000, 2001; Coolidge and Wynn 2005) or—put differently—working attention. Four main components of working memory have been identified.

1. The panmodal controller is a central executive component (attentional control system or supervisory attentional system) that may be represented by a single, unitary, executive controlling system or multiple, segregated, information-processing modules of varying functions. These functions may include attention, active inhibition, decision making, planning, sequencing, temporal tagging, and the updating, maintenance, and integration of information from two subsystems.

2. The episodic buffer is a short-term, multimodal mnemonic interface between working-memory systems and long-term memory. Retrieval from the buffer into awareness allows multiple sources of information to be compared and con-

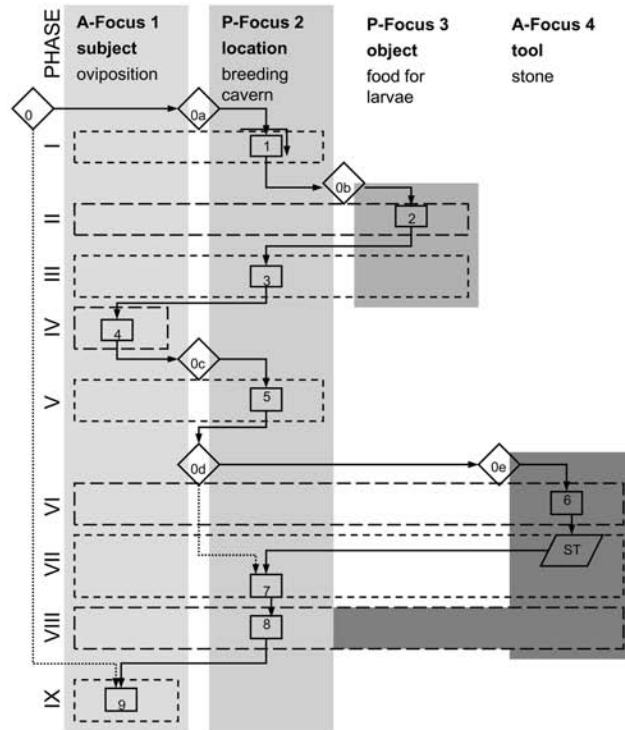
trasted simultaneously and results in sophisticated problem solving and the planning of future behavior.

3. The phonological storage is the first of two subsystems or content domains that contains two elements, a short-term phonological storage of sounds and an articulatory loop that maintains and rehearses information either vocally or subvocally.

4. The visuospatial sketch pad is the second of the two subsystems or content domains that maintains and integrates visual (“what” information, i.e., objects) and spatial (“where” information, i.e., locations in space) elements and operates as a means to refresh working memory by rehearsal.

Working memory serves to focus attention by maintaining memory representations (plans of action, short- or long-term goals, or task-relevant stimuli) in a conscious state despite interference or response competition (Kane and Engle 2000, 2002, as cited in Coolidge and Wynn 2005). The central executive component takes control when novel tasks are introduced, when preexisting habits have to be overridden, or when task-relevant decisions must be made; it is thus linked to innovation. Working memory is also involved in language comprehension and production by influencing sentence complexity and length. The model of working memory used by Coolidge and Wynn (2005), however, is disputed by psychologists in several aspects (Barnard 2010; Beaman 2010; Engle 2010; Martín-Loeches 2010, all in this issue).

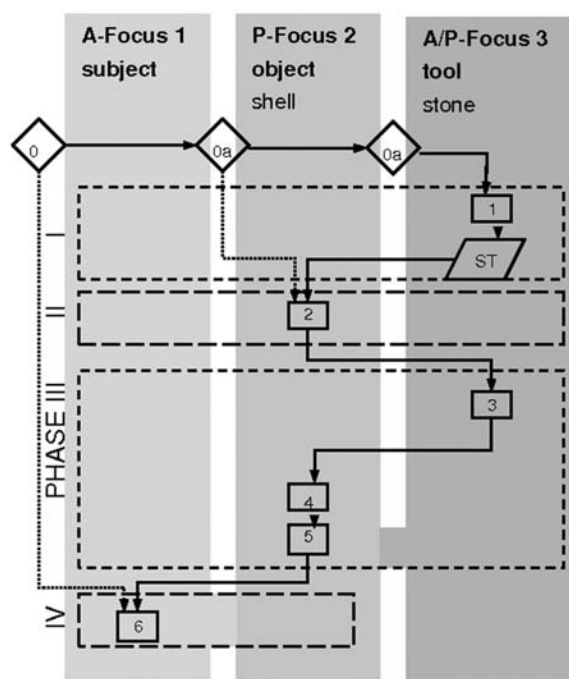
The evolution of working memory cannot be examined



Use of stone to close breeding cavern by *Ammophila* and *Sphex* (after Beck 1980 )

- 0. Perception of basic need: preparing a place for oviposition
- 0a. Perception of sub-problem 1: cavern needed
- PHASE I: digging a cavern**
- 1. Digging a cavern
- 0b. Perception of sub-problem 2: food for larvae needed
- PHASE II: search for food**
- 2. Search for adequate nutrition for larvae
- PHASE III: transport of food**
- 3. Transport of food item to cavern
- PHASE IV: oviposition**
- 4. Oviposition
- 0c. Perception of sub-problem 3: closing of the cavern
- PHASE V: closing of the cavern**
- 5. Closing of the cavern with sediment
- 0d. Perception of sub-problem 4: compression of sediment necessary
- 0e. Perception sub-problem 5: tool for compression needed
- PHASE VI: search for tool**
- 6. Search for appropriate stone
- PHASE VII: transport of tool**
- 7. Transport of stone to cavern
- PHASE VIII: compression of sediment**
- 8. Compression of sediment with stone
- PHASE IX: satisfaction of need**
- 9. Need satisfied

Figure 2. Cognigram of the use of a stone to close a breeding cavern by wasp species of the genus *Ammophila* and *Sphex*.



Use of stone to open shells by *Enhydra lutris* (after Hall and Schaller 1964 )

0. Perception of basic need: feeding  
 0a. Perception of sub-problem 1: access to shells  
 0b. Perception sub-problem 2: tool necessary to open shells

**PHASE I: search for tool**

1. Search for appropriate stone

**PHASE II: transport of tool**

2. Transport to shell and to water surface

**PHASE III: cracking the shell**

3. Positioning of stone on the chest  
 4. Holding the shell in the paws  
 5. Bashing of shell on the stone (several times)

**PHASE IV: satisfaction of need**

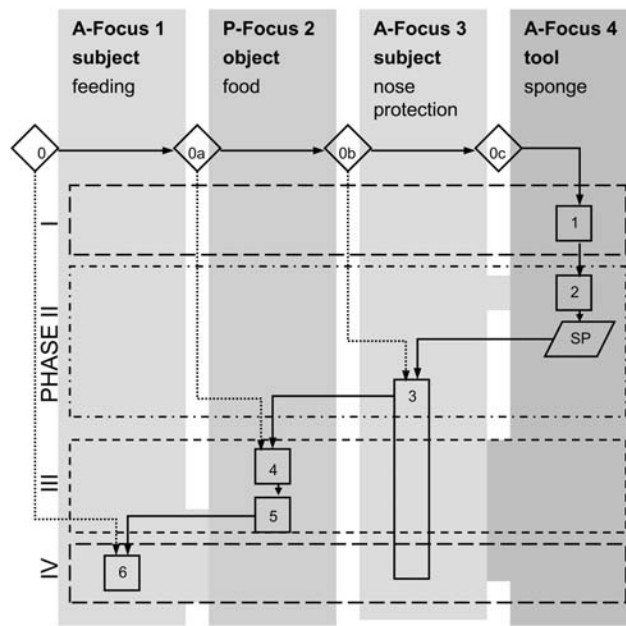
6. Consumption of the meat

Figure 3. Cognigram of the use of a stone to open shells by *Enhydra lutris*.

using the same neuropsychological methods applied to living individuals on which the models were built. To trace the development of the executive brain functions and probable associates, material outcomes need to be identified and revealed in an archaeological context—which is an extremely selective database in itself (Haidle 2007). The indicators of modern human cognition and behavior commonly stressed by archaeologists do not help delineate a model of the evolution of working memory for two reasons. First, the causal relation of their emergence to an extension of working memory has yet to be proved, and second, the static and narrow nature of these indicators does not allow evolutionary developments to be followed. This leads to the question, what other evidence can be studied to get a clearer picture of the

development of the executive functions during the course of human evolution? The answer is a measure of cognitive complexity, flexibility, and decision making: the problem-solution distance.

Cognitive processes materialize partially in artifacts and to a lesser extent even fossilize as such. Only a small portion of the cognitive potential of a species can be detected in the objects used. Nonetheless, the material remains constitute the largest database available for the study of applied cognitive capacity of fossil hominins, and they make it possible to compare a segment of the behavior of nonhuman living species. A basic trait of all object behavior is the increased distance between problems and solutions. In his famous experiments with hens, dogs, and especially chimpanzees in the early twen-



Use of a sponge as nose protection by *Tursiops sp.* (after Krützen et al. 2005)

- 0. Perception of basic need: feeding
- 0a. Perception sub-problem 1: access to food
- 0b. Perception sub-problem 2: sediment of sea floor hurts nose
- 0c. Perception sub-problem 3: protection necessary

**PHASE I: search for tool**

- 1. Search for appropriate sponge

**PHASE II: production of tool**

- 2. Detaching of sponge
- 3. Putting it over the nose / protection

**PHASE III: scaring up prey / use of tool**

- 3. Putting it over the nose / protection
- 4. Scaring up prey from ocean floor
- 5. Catching the food

**PHASE IV: satisfaction of need**

- 6. Consumption

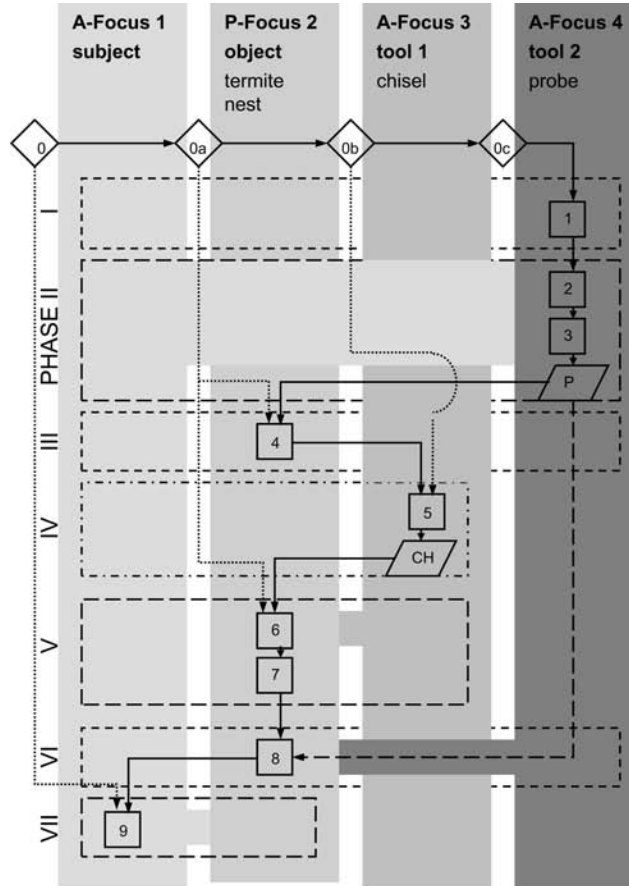
Figure 4. Cognigram of the use of a sponge as nose protection by *Tursiops sp.*

tieth century, Wolfgang Köhler (1926) recognized tool behavior as an extension of the process of indirect thinking. If tool use is considered to solve a problem, then the immediate desire—getting the kernel of the nut, for example—must be set aside, or inhibited, and replaced by one or several intermediate objectives, such as finding or producing an appropriate tool. Thus, at least in the short term, thinking must depart from the immediate problem and shift to abstract conceptualizations of potential solutions, which results in sequences of physical actions with objects appropriate to achieve a solution in the near future.

The distance between the initial problem and the final solution varies markedly in different object behaviors. The solution can be close to the need, as when marine snails of the

genus *Tegula* use a nearby stone of the correct size and weight as a counterbalance to right themselves onto their plantar bases (Weldon and Hoffmann 1975). But the indirect road to satisfaction may also be extended through the establishment of several intermediate goals (see Beaman 2010). Sanz, Morgan, and Gullick (2004), for example, describe the extraction of termites by the Moto group, a chimpanzee population in the Republic of Congo, and their search for, manufacture of, and subsequent use of a set of different artifacts. Besides differences in cognitive complexity, the intraspecific comparison of the interspecific variability of the object behavior and the problem-solution distances yields information about a species' cognitive flexibility. New Caledonian crows (*Corvus moneduloides*) reveal a stunning diversity in tool man-





Use of a tool-set to extract termites by *Pan troglodytes* (after Sanz et al. 2004)

- 0. Perception of basic need: feeding
- 0a. Perception of sub-problem 1:  
open termite nest / extract termites
- 0b. Perception sub-problem 2: tool necessary to open nest
- 0c. Perception of sub-problem 3: tool necessary for probing

**PHASE I: manufacture of probe I**

- 1. Search for appropriate twig

**PHASE II: manufacture of probe II**

- 2. Detaching the twig
- 3. Shortening / removal of leaves / fraying of brushtip

**PHASE III: transport of probe**

- 4. Transport of probe to termite nest

**PHASE IV: search for chisel**

- 5. Selection of chisel on site

**PHASE V: opening the termite nest**

- 6. Pushing with chisel (several times)
- 7. Inspection of chisel

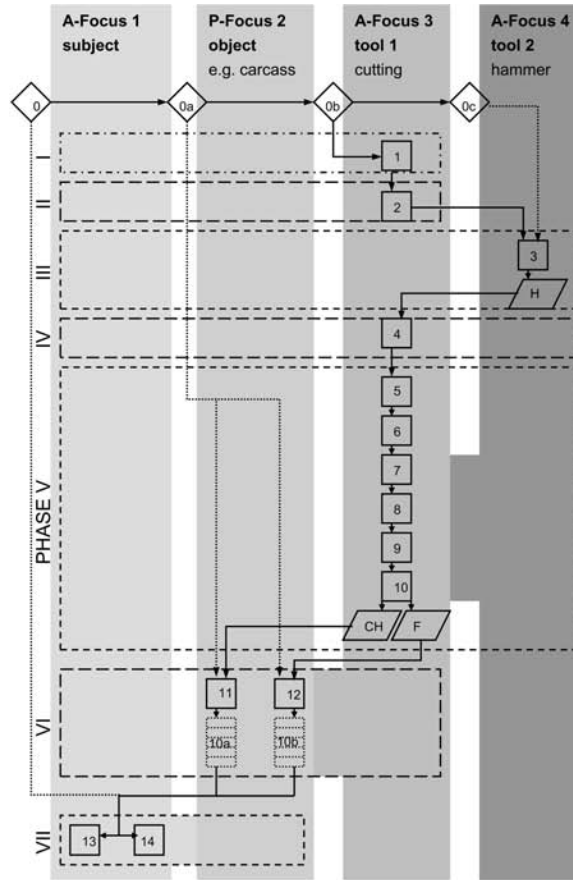
**PHASE VI: probing for termites**

- 8. Extraction of termites with probe

**PHASE VII: satisfaction of need**

- 9. Consumption

Figure 5. Cognigram of the use of a tool set to extract termites by *Pan troglodytes*.



**Use of an Oldowan tool to cut meat by *Homo sp.***

- 0. Perception of basic need: hunger
- 0a. Perception sub-problem 1: need of meat
- 0b. Perception sub-problem 2: need of cutting tool
- 0c. Perception sub-problem 3: need of tool for production

**PHASE I: gathering raw material for tool 1**

- 1. Search for raw material / Gathering

**PHASE II: transport of raw material for tool 1**

- 2. If necessary, transport to workshop

**PHASE III: search for tool 2**

- 3. Search for hammerstone

**PHASE IV: transport of tool 2**

- 4. Transport of hammerstone to raw material / workshop

**PHASE V: use of tool 2 / production of tool 1**

- 5. Positioning of individual
- 6. Positioning of raw material and hammerstone
- 7. Knapping (debitage)
- 8. Rotating core
- 9. Knapping (retouch)
- 10. Knapping (flake)

**PHASE VI: use of tool 1**

- 11. Use of chopper, or
- 12. Use of flake

**PHASE VII: satisfaction of need**

- 13. Direct consumption
- 14. Indirect consumption (e.g. sharing, feeding)

Figure 6. Cognigram of the use of an Oldowan tool to cut meat. Note the effective chain of tool 2 on tool 1 on the object.



Figure 7. Cognigram of the use of a wooden spear to hunt horses based on the Schöningen 13 evidence. (Figure continues on following two pages.)

**Production and use of a spear by *Homo heidelbergensis***

00. Perception basic need (in principle, semi-acute): hunger  
 00a. Perception subproblem 1 (in principle, semi-acute): hunt prey  
 00b. Perception subproblem 2 (in principle, semi-acute): need of spear (tool 1)  
 00c1. Perception subproblem 3A (semi-acute): need of handaxe to cut down tree (tool 2):  
 quality A  
 00c1. Perception subproblem 3B (semi-acute): need of handaxe to cut down tree (tool 2):  
 quality B  
 00d. Perception subproblem 4 (semi-acute): need of flake tool (tool 3) to work wood  
 0e. Perception subproblem 5 (acute): need of hard hammerstone (tool4) to produce tool 3 and  
 work on tool 2  
 0f. Perception of subproblem 6 (semi-acute): need of a soft hammerstone (tool 5) for retouch  
 of tool 2  
**PHASE I:** Search for tool 5 (soft hammerstone)  
**PHASE II:** Transport tool 5 / Search for tool 4 (hard hammerstone)  
**PHASE III:** Transport tools 4, 5 / Search for raw material for tools 2 and 3  
**PHASE IV:** Production tool 2 / Use tool 4 → roughout of handaxe  
**PHASE V:** Production tool 2 / Use tool 5 → thinning  
**PHASE VI:** Production tool 2 / Use tool 5 → retouch  
 00-00f. Perception of basic need, subproblems 1-6 (in principle)  
 0g. Perception subproblem 7 (acute): secure tools at site  
**PHASE VII:** Transport of tools 2, 4, 5 and raw material to site  
**PHASE a-z:** several other activities (not related, not specified)  
 00-00b. Perception basic need, subproblems 1-2 (in principle, semi-acute)  
 0c. Perception subproblem 3 (acute)  
**PHASE VIII:** Search for raw material for tool 1 / Transport tool 2  
 00-00b. Perception of basic need, subproblems 1-2 (in principle)  
 0c. Perception subproblem 3 (acute)  
 0g. Perception subproblem 7 (acute): secure tools at site  
**PHASE IX:** Transport tool 2 to site  
**PHASE a-z:** several other activities (not related, not specified)  
 00-00b. Perception basic need, subproblems 1-2 (in principle, semi-acute)  
 0c. Perception subproblem 3 (acute)  
**PHASE X:** Search for raw material for tool 1 / Transport tool 2  
**PHASE XI:** Production tool 1 / Use tool 2 → cut down tree  
**PHASE XII:** Production tool 1 / Use tool 2 → roughout of blank of spear  
 00-00b. Perception basic need, subproblems 1-2 (in principle, semi-acute)  
 0c. Perception subproblem 3 (acute)  
 0g. Perception subproblem 7 (acute): secure tools at site  
**PHASE XIII:** Transport blank 1 and tool 2 to site  
**PHASE a-z:** several other activities (not related, not specified)  
 00-00a. Perception basic need, subproblem 1 (on principle, semi-acute)  
 00b1. Perception subproblem 2A (semi- acute): quality A  
 00b2. Perception subproblem 2B (semi- acute): quality B  
 0d-e. Perception subproblem 4-5 (acute)

Figure 7. (Continued)

ufacture with regard to raw material and production techniques, ranging from shaping of hooks out of twigs (Hunt and Gray 2004) and ripping off sections of barbed *Pandanus* leaves (Hunt and Gray 2003) to bending wire into hooks (Weir, Chappell, and Kacelnik 2002). However, the birds' object behavior is limited to a clearly defined context, that of extracting invertebrates from holes in dead wood, and a specific problem-solution distance. Both aspects are common to all forms of their object use.

Chimpanzees (*Pan troglodytes*), by contrast, use tools in a

broad variety of situations: social play, to get access to food, in personal hygiene, to investigate strange things, to reduce frustration, for defense, as a means of communication, in imposing behavior, for self-stimulation, and as an aid in locomotion. Twigs, branches, sticks, stones, leaves, stems of grasses and leaves, and strips of bark are the raw materials that they use and modify in different ways and by different techniques. A tool type can be used to solve different kinds of problems; to satisfy a certain need, a tool may be chosen from several variants. A set of different tools can be used

**PHASE XIV:** Production tool 3 / Use tool 4  
**PHASE XV:** Production tool 1 / Use tool 3 → rework bases of branches  
**PHASE a-z:** several other activities (not related, not specified)  
 00-00a. Perception basic need, subproblem 1 (in principle, semi-acute)  
 00b1. Perception subproblem 2A (semi-acute): quality A  
 00b2. Perception subproblem 2B (semi-acute): quality B  
 0d-e. Perception subproblem 4-5 (acute)  
**PHASE XVI:** Production tool 3 / Use tool 4  
**PHASE XVII:** Production tool 1 / Use tool 3 → remove bark, rework form  
**PHASE a-z:** several other activities (not related, not specified)  
 00-00a. Perception basic need, subproblem 1 (in principle, semi-acute)  
 00b1. Perception subproblem 2A (semi-acute): quality A  
 00b2. Perception subproblem 2B (semi-acute): quality B  
 0d-e. Perception subproblem 4-5 (acute)  
**PHASE XVIII:** Production tool 3 / Use tool 4  
**PHASE XIX:** Production tool 1 / Use tool 3 → rework form, carve tip  
**PHASE a-z:** several other activities (not related, not specified)  
 0-0b. Perception basic need, subproblems 1, 2 (semi-acute, acute)  
 0c. Perception subproblem 3 (semi-acute): need of tool 2 (handaxe) to butcher prey  
 00f. Perception subproblem 6 (semi-acute): need of tool 5 for retouch of tool 2  
**PHASE XX:** Search for prey / Transport tools 1, 2, 5  
**PHASE XXI:** Satisfaction of need not successful → frustration  
 00-00c + f. Perception basic need, subproblems 1, 2, 3 and 6 (semi-acute, in principle)  
 0g. Perception subproblem 7 (acute): secure tools at site  
**PHASE XXII:** Transport tools 1, 2, and 5 to site  
**PHASE a-z:** several other activities (not related, not specified)  
 0-0b. Perception basic need, subproblems 1, 2 (semi-acute, acute)  
 0c. Perception subproblem 3 (semi-acute): need of tool 2 (handaxe) to butcher prey  
 00f. Perception subproblem 6 (semi-acute): need of tool 5 to resharpen tool 2  
**PHASE XXIII:** Search for prey / Transport tools 1, 2, 5  
**PHASE XXIV:** Hunt / Use tool 1 / Transport tools 2, 5 → kill animal  
**PHASE XXV:** Butcher prey / Use tool 2 A → Remove skin  
 0-0a. Perception basic need, subproblem 1 (acute)  
 0c1. Perception subproblem 3A (acute): need of tool 2 (handaxe) to break open carcass: quality A  
 0c2. Perception subproblem 3B (acute): need of tool 2 (handaxe) to break open carcass: quality B  
 0f. Perception subproblem 6 semi-acute): need of tool 5 (soft hammerstone) to sharpen tool 2  
**PHASE XXVI:** Retouch of tool 2 / Use tool 5  
**PHASE XXVII:** Butcher prey / Use tool 2 AB → break open and butcher carcass  
**PHASE XXVIII:** Satisfaction of need  
 00. Perception basic need (semi-acute)  
 00a-c, f. Perception subproblem 1-3 and 6 (semi-acute, in principle)  
 0g. Perception subproblem 7 (acute): secure prey and tools 1, 2, 5 at site  
**PHASE XXIX:** Transport of parts of prey and tools 1, 2, 5 to site  
**PHASE a-z:** several other activities (not related, not specified)

Figure 7. (Continued)

sequentially to reach an aim (Haidle 2008a). Chimpanzees show a distinct flexibility in all aspects of cognitive behavior, including the contexts and the problem-solution distances. The more flexible objects are employed by a species, by a group, and most critically by an individual, the more decisions must be made to find a convenient solution dependent on an evaluation of the problem. Thus, a detailed examination of both the object behavior and the inherent problem-solution distance serves to illuminate several general aspects of the executive functions of the postulated working memory.

To compare the various forms of object behavior of different animal species with Paleolithic human populations, equivalent and self-contained study units need to be identified. Every unit comprises a behavioral process initiated by an internal or external stimulus (need, problem) and terminated by the positive or negative satisfaction of the need (the solution to the problem). Thus, it is insufficient to compare the nut cracking of chimpanzees using a stone hammer with an Oldowan tool (Joulian 1996), because the trigger for the manufacture and the final aim of the Lower Paleolithic

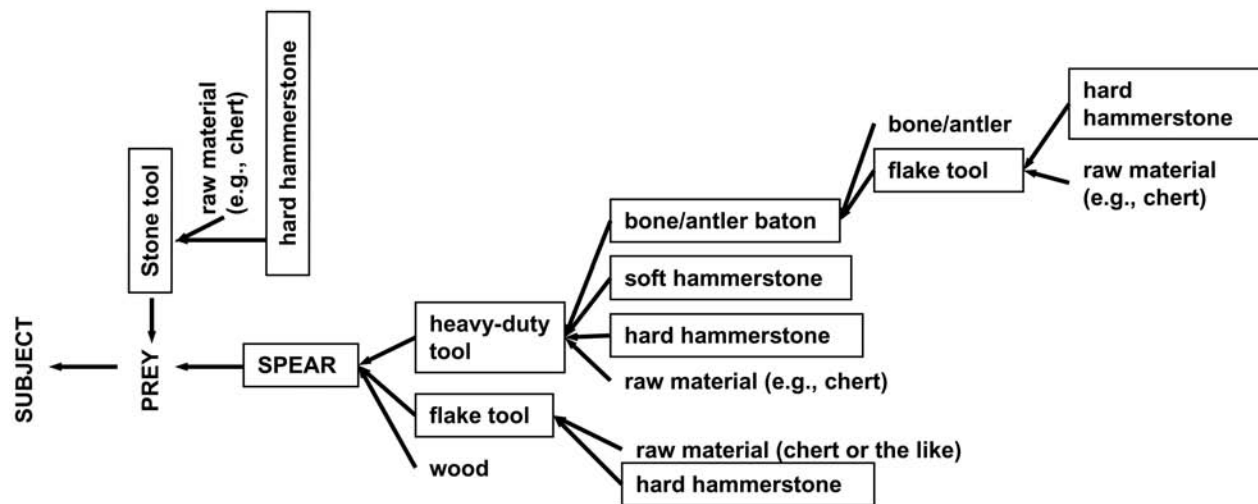


Figure 8. Effective chain of raw materials and tools that can be used to hunt with a simple spear. Boxes indicate small operational units that can be put together in a modular way.

tool are not mentioned. Instead, the nut cracking of chimpanzees has to be contrasted with a complete behavioral process that starts with a hypothetical need, the desire to eat some meat. The process continues with the perception of a first subneed to have a cutting tool and a second subneed to possess a hammerstone to knap the tool, the search for the required elements to produce the cutting tool, its actual manufacture, and its application on a carcass. The process culminates with the satisfaction of hunger. Only in the combination of the different elements of mental representations and physical operations can the final aim be reached. If an individual is unable to conceptualize a tool for termite fishing, it makes no sense for it to look for a thin and flexible twig in the bushes 5 m away from the termite mound.

Viewed separately from each other, much information about cognitive aspects—such as goal-oriented decision making, sequencing of actions, or flexibility in application of problem-solution concepts—is lost. To integrate these aspects, the complete study units are coded in cognigrams, which represent an enhancement on the basis of the concept of *chaîne opératoire* (Pélégriin, Karlin, and Bodu 1988; Schlanger 1994). In cognigrams, the various single-action steps, which are pooled in larger phases of action, are assigned to different attention foci. These include all separate, discrete elements of attention that take part in the sequence and include the acting subject, objects to be treated, locations, and actively operated tools (fig. 1); they may be active agents or passive elements. The different attention foci are initiated by the probable perceptions of needs and problems that start the actions. Additionally, effects of one focus on another are also represented in cognigrams (Haidle 2006, 2009). In the following, some examples of different animal and hominin tool behavior coded in cognigrams will show the potential of this analytical

tool to uncover and accentuate executive functions of the working memory, which include focusing attention, sequencing, planning, temporal tagging, and integrating information from the visuospatial sketch pad.

## From Unmodified Stones . . .

Object behavior per se does not necessarily require high cognitive capacities; wasps of the genus *Ammophila* and *Sphex*, for example, show a simple stereotype, instinctive form. In the process of oviposition, they dig caverns, where they lay eggs and put some of their prey to feed their offspring. Then they seal their subterranean nests with sediment and finally compress it with the help of small stones, lumps of earth, pieces of wood or bark, or seeds (Beck 1980:17; Becker 1993: 28–29). In the cognigram (fig. 2) the process looks fairly elaborate, yet this is because of the embedding of the use of the tool in the complete oviposition process. In this process, which is completely driven by instincts, the attention foci lie with the subject and its basic need to reproduce in a genetically predetermined way and with the breeding cavern, in part supplemented by a focus on the appropriate prey and, in the end, by a focus on the tool needed for compression. It can be assumed that the complete process is not understood or present as a whole in the form of a mental template. Rather, it is urged along step by step by new stimuli (marked by the rhombus in the cognigram) until satisfaction occurs, in that the process is completed and no new stimulus arises. In this object behavior, the effect of a working memory is minimal.

Sea otters (*Enhydra lutris*), by contrast, show simple but clearly cognitive object behavior. In a feeding context, the animals dive to the ocean floor to pick up an appropriate stone needed to open mollusks and other food items. Together

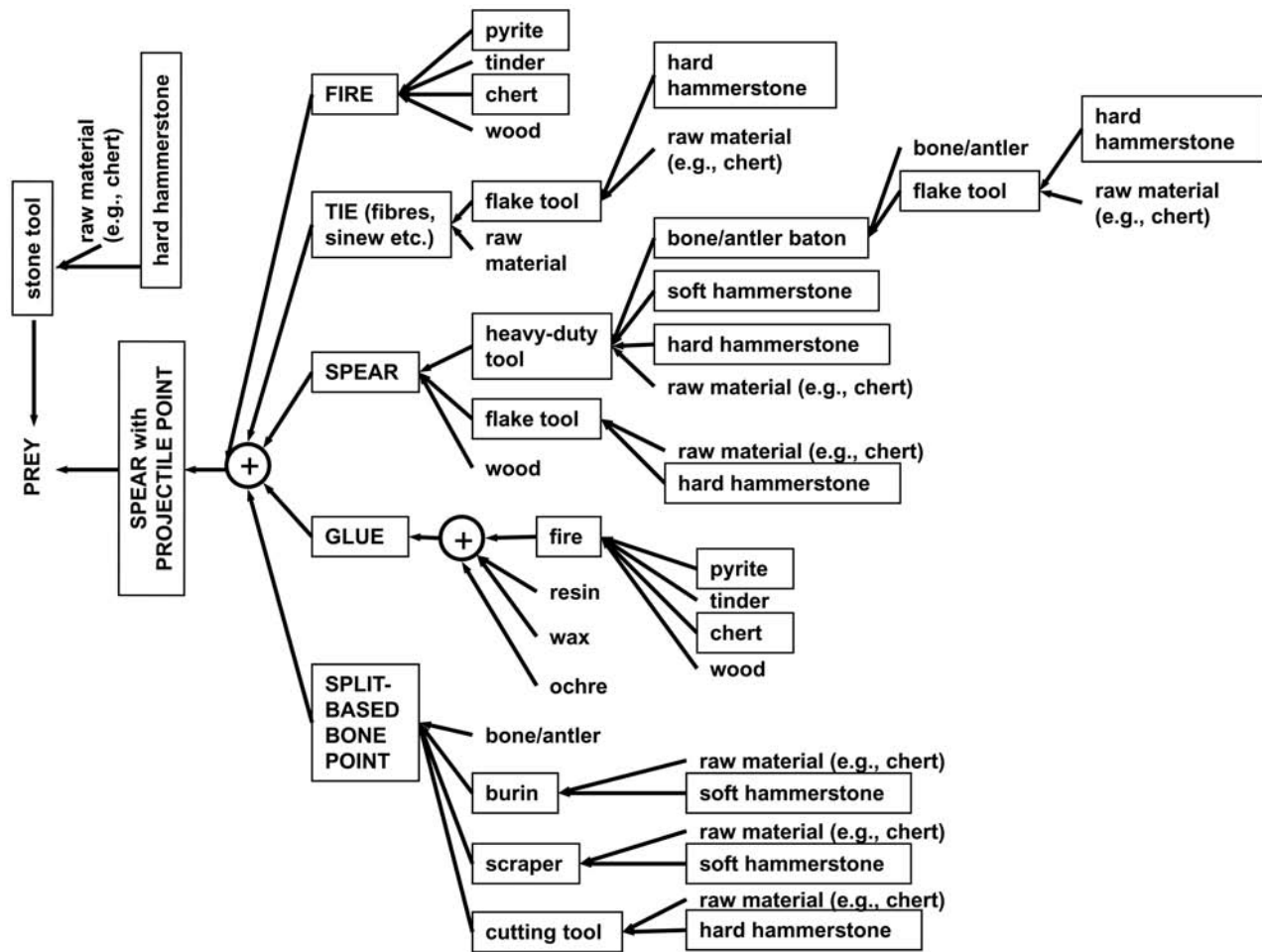


Figure 9. Effective chain of raw materials and tools that can be used to hunt with a spear with a split-based bone point. Boxes indicate small operational units that can be put together in a modular way.

with the stone and a mussel, an otter surfaces, rolls on its back, balances the stone on its chest, and pounds the mussel against the stone several times until it breaks. The stones can be transported during several dives and reused, even though some intervening dives with the stone yielded prey that did not need to be pounded. These dives can be followed by a later dive, with subsequent reuse of the stone to open a mussel. This behavior is performed with several variants: different food items are pounded against the stone or rarely against an abalone shell or clam shell. While the Californian population uses the tools regularly, in the Aleutian population, only the subadults use stones to open the small mussels of the region, and the old individuals use them to pound sea urchins (Beck 1980:41–43; Hall and Schaller 1964). In the cognigram of this stone tool behavior (fig. 3), all three foci are open at the same time. After the consumption of the meat, the whole process or just part of it may be repeated, starting with the second action. In addition to this object behavior, otters also use

stones to hammer abalone from the substrate and wrap kelp around themselves to gain stability during periods of rest and sleep (Beck 1980:43–44). Regarding the necessary working memory, the object behavior of sea otters includes the management of three foci during the complete process, the suitable sequencing of actions, decision making concerning the necessity of tool use and the right size of the tool, and the integration of object and spatial information.

While tool use in sea otters is directly linked to satisfying the basic need of feeding, the tool use observed in a Western Australian population of bottlenose dolphins *Tursiops* sp. serves an accompanying parallel need. To scare prey up from the ocean floor, the animals nuzzle the sediment, an action that can hurt their sensitive noses. A group of closely related females and a few males employs sponges over their noses to protect them during feeding. This feeding behavior is only one of several that are probably neither genetically nor ecologically induced (Krützen et al. 2005; Sargeant et al. 2007;

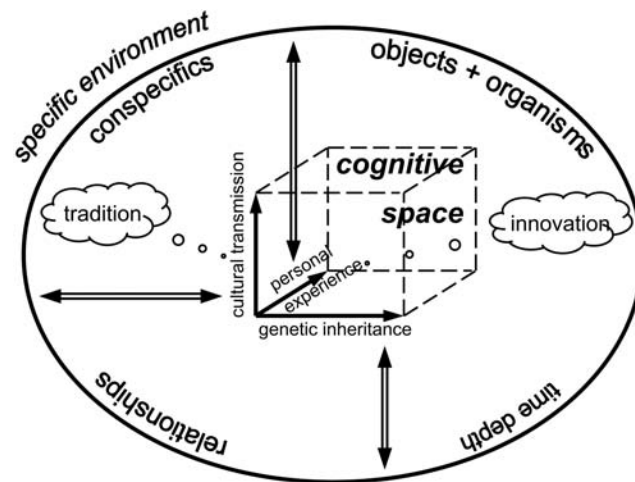


Figure 10. Individual cognitive space within the specific environment.

Smolker et al. 1997). Figure 4 shows the cognitive peculiarity of this behavior. Instead of subordination of all other foci to one subject focus, here two subject foci—feeding and nose protection—exist side by side, although not equivalently. The tool behavior in nose protection is barely interwoven with the feeding processes and can easily be abandoned without changing the process of the main purpose. The tool has an effect only on A(ctive)-focus 3 “nose protection,” and the feeding process works in the same way if foci 3 and 4 are omitted together with the action steps 1–3. The cognigram of the feeding process (left half) does not change if the process of nose protection (right half) is removed. An enhancement of the executive functions of the working memory can be seen in the integration and management of two parallel needs and the deduced subprocesses.

Most tool-using animals employ only one tool per behavioral unit; chimpanzees, however, are able to subsequently use several different tool types to solve distinct subproblems in one activity process. Sanz, Morgan, and Gullick (2004) and Sanz and Morgan (2007) report for the Moto group of *Pan troglodytes troglodytes* in the Republic of Congo the application of two different two-tool sets in tasks to extract termites from subterranean and elevated termite nests, as well as the use of up to three different tools in getting access to honey. The most interesting cognitive characteristic of this form of tool use in termite extraction is the chimpanzees’ realization of the need for two different tools to solve the problem from the beginning of the process on (fig. 5). Appropriate twigs for fishing probes are sought and manipulated in several ways before the chimpanzees approach the nest and look for a suitable perforator, which sometimes also has to be modified. Thus, four foci are open and have to be managed in the right sequence to reach the final goal. The different components of the problem-solution process are perceived in advance, indicating another executive function of working memory:

planning. The chimpanzees often reuse perforators that were left on site previously. It seems that they expect perforators to be next to the termite nests, a cognitive capacity that has been extensively studied by Boesch and Boesch (1984) for stone hammers used to open nuts. Information from long-term memory is integrated in processes of working memory and implies the possible existence of an episodic buffer.

In the use of an Oldowan tool to process a carcass, there are also two tools needed to solve the basic problem. Yet contrary to the use of the two sets used by chimpanzees to extract termites, in which both tools were applied to the same object, the termite nest, the two tools used in the processing of a carcass are applied in an effective chain (fig. 6). The first tool, a hammerstone, is used to knap the second, the cutting tool (be it a heavy-duty tool or a flake), which is then applied to the carcass. This so-called secondary tool use (Kitahara-Frisch 1993), which has been present in hominin stone tool production and used since at least 2.6 million years ago, constitutes a further extension of the problem-solution distance by producing a tool with a tool and handling two objects not subsequently but simultaneously. By physically and mentally coping not only with several elements of an action but also with different effects on several of these elements, the integrative capacity of the executive functions of working memory is clearly enhanced. Up to now, secondary tool use has not been unquestionably proven in wild chimpanzees or other animals. Rare evidence remains highly disputed either in the de facto use of a second tool to produce the first, as in brush sticks (Takemoto, Hirata, and Sugiyama 2005), or in the evaluation of the items as independent tools, as in a stone used as a wedge to level a stone anvil for nut cracking (Matsuzawa 1996).

In the course of the first 1 million years of the Lower Paleolithic, the potential spatial and temporal distance of primary raw-material acquisition and final use ranged from close



by to generally not more than 2–3 km away (Plummer 2004), with evidence for the use of a small amount of raw material stemming from natural outcrops at least 15–20 km away (Blumenshine et al. 2003). At sites on the west coast of Lake Turkana dated to 1.8–1.7 Ma, Harmand (2005) observed large, barely worked blocks that might have served as raw-material stock. If we consider the larger spatial and temporal distances that extended further in later Lower Paleolithic times, it is likely that the behavioral process of the use of an Oldowan tool to process a carcass commenced only partially from an acute and urgent need followed by immediate actions until the satisfaction of the need. Rather, the process started with the perception of a subacute need followed by actions that may have been interrupted by other problems, and their solution was picked up again afterward. During these interferences, the memory representations of the problem-solution unit must have been consciously or subconsciously present or, in the case of raw-material stocks, stored in long-term memory. Acting with subacute needs—an issue perceived to become a problem in the future—not only implies planning but also hints at some form of time tagging (known in the psychological literature as “sequential memory”). Problems are no longer perceived or solved only in the immediate or extended present but beyond. Cognitive time depth is growing at least in the future direction and probably also to the past, thus making reflections about past events and actions possible.

### . . . to Complex Composite Tools

In comparing even the most sophisticated Lower Paleolithic stone tools with simple wooden spears such as those from the late Lower Paleolithic sites of Clacton (Oakley et al. 1977) or Schöningen 13 (Haidle 2008a; Thieme 1997, 1999), a great leap forward can be detected in the problem-solution distance (fig. 7). In between, there are gradual extensions of the problem-solution distance that can be traced in the preserved artifact record (Haidle 2006). These are mainly represented by stone tools with a limited spectrum of options for their manufacture and use. It is likely, however, that in the overwhelming repository of rarely preserved material remains, more surprises like that of the spears remain hidden. The production of wooden spears is regarded both as quite demanding in terms of the skills and knowledge necessary to give the tool the proper qualities for use and as a simple process, with a few different activities, that takes half a day to complete. The second idea originates in the common basic assumption that archaeological artifacts should be taken as independent items, detached from a larger problem-solution context (see above; Joulian 1996). In this tradition, Veil (1991) produced experimental reproductions of a simple wooden lance from the Middle Paleolithic site of Lehringen and measured the time of manufacture. However, before starting, he had the wooden raw material, as well as the necessary stone tools, on hand. Nonetheless, it took 4.5–5.5 hours to finish the lance, from cutting down the tree, removing the side

branches, smoothing the bases of the branches, stripping off the bark, and reworking the form and surface of the spear to the final trimming of the tip. However, for a direct comparison of the mental and physical effort to produce and use a wooden spear with that used to produce other tools, Veil's incomplete production process has to be imbedded into a complete process from a basic problem to its ultimate solution.

The cognigram of a Lower Paleolithic spear presented in figure 7 can be no more than hypothetical, yet it is based on realistic assumptions drawn from Veil's (1991) experiments and supported by the detailed analysis of the 300,000–400,000-year-old Schöningen spears (Thieme 1999). These are supplemented with some commonsense assumptions about phases of raw-material procurement, transport of different elements, and the production of tools, as well as about repeated interruptions of the process by other urgent needs. Figure 7 includes the main foci and phases in a process that might take several days to reach its final goal. For the sake of clarity, the single-action steps are omitted. Thus, the cognigram presented here is markedly simplified and abstracted. Its operational sequence comprises an effective chain of a minimum of five foci: the soft or hard hammerstones (1) to produce a handaxe or other heavy-duty tool and a flake tool (2) to cut down the tree and carve the spear (3) to kill the prey (4) to satisfy the subject's need (5). If a bone or antler baton were included in the stone tool production, the effective chain (fig. 8) would be accordingly lengthened.

The operational sequence of the Schöningen spear is extremely extended in both duration and complexity. To think through and follow it from the perception of a subacute basic need (hunger for meat) to its final satisfaction would be very demanding. This high level of complexity in tool behavior is possible only by decoupling satisfaction and basic need such that the manufacture and curation of tools can become aims and satisfactions in and of themselves, independent of current basic needs (see also Beaman 2010). The resulting small operational units, each autonomous with its own intermediate aim, can be assembled in a modular way within different operational sequences. This modular way of handling tools enables the combination of several operational units side by side or in an effective chain and thus allows a level of behavioral complexity—for example, in complex tools such as spears with hafted projectile points—barely conceivable without the modular simplification (Haidle 2006, 2009).

Thus, from one perspective, artifacts—at least from the late Lower Paleolithic on—may be seen as independent operational units, in a way similar Joulian's (1996). Yet from another perspective, this yields only a fraction of the possible information. An Aurignacian split-based bone or antler point, for example, must be viewed not only as a simple bone or antler tool that was produced with the help of some other stone tools but also as part of a complex set of operational units that form a spear with a bone projectile point to hunt for prey that is needed to satisfy a feeling of hunger (fig. 9;

for detailed discussions of composite tools, see Ambrose 2010; Wadley 2010, both in this issue). Composite tools such as spears with projectile points are consistent with development based on the modular combination of several operational units. The concept of composite tools developed gradually, and Aurignacian split-based points represent earlier results of this development. The oldest evidence of hafting comes from four split-based tools from Schöningen 12, dated to oxygen isotope stage 11, as old or even slightly older than the spears from Schöningen 13, made of fir wood and interpreted as clamp shafts (Thieme 1999). A more advanced version of a composite tool with the use of specific hafting material can be deduced from two pieces of birch tar from Königsau dated to around 80,000 BP, with impressions of stone tools and wood, probably of a handle (Koller, Baumer, and Mania 2001). Bitumen residues on Levallois points from the late Middle Paleolithic at Umm el Tlel indicate their use as hafted scrapers (Boëda et al. 1996). A Levallois point from the same site was applied as a projectile point, a fragment of which was embedded in the vertebra of a wild ass (Boëda et al. 1999). Fracture patterns and residue remains on Middle Stone Age artifacts from Sibudu Cava, KwaZulu-Natal, South Africa, are interpreted as traces of hafting of projectile points to wooden spears with the help of plant fibers, resin, fat, and ochre (Lombard 2005; Wadley 2010). Evidence for composite tools significantly earlier than the European Upper Paleolithic is constantly growing in Africa, as well as in West Asia and Europe.

## Modular Organization, Working Memory, and the Evolution of Modern Behavioral Capacity

The modular organization of thought-and-action processes constitutes an important simplification of complex and multifaceted operations. If an individual uses a hierarchical system of operational units with subordinate phases and action steps, operations become easily possible that would otherwise hardly be considered (see Beaman 2010). The cognitive evolution toward the modular organization of object behavior proceeded gradually. Simple forms are limited to fixed problem-solution units with small problem-solution distances and little flexibility in any aspect. Several animal species and archaeological artifacts show extensions of different aspects in object behavior, of expansions of the problem-solution distance concerning, for example, the modification of the objects used, the number of attention foci, the management of parallel needs, the subsequent use of different tools, the anticipation of the necessity of several tools, the number of elements in an effective chain, the handling of two objects simultaneously, the perception and pursuit of subacute needs, and even the bridging of interruptions to the operational process by competing problems. In addition, these extensions offer an increase of flexibility in different solutions for one problem; in

diverse needs met with one solution; in the exact application of specific action steps, phases, and the entire course of the operational sequence; in contexts in which problems are perceived; in the combination of separate tools into one process; and in the combination of raw materials, manufacturing techniques, tool types, and use.

The modular, hierarchical organization of operational processes is a consequence of all these extensions, allowing a range of cognitive and behavioral complexity and flexibility as it is basic to modern human behavior. The form in which this potential is expressed depends mainly on cultural factors. By producing tools, humans do more than just make a given environment increasingly manageable; they also create material and cognitive elements of their specific environment that expand with the increasing dissociation of subsistence constraints, perceived problems, and available solutions. The more tools and their manufacture can be dissociated from immediate subsistence aims, the more problems become soluble. The handling, manipulation, and use of aesthetic objects and the manufacture of ornaments, parietal and mobile art, and musical instruments are part of the possible outcome of this dissociation, though not necessarily one with material manifestations in the archaeological record. The ways in which the modular organization of thought-and-action processes and the potential flexibility and the decoupling of subsistence constraints, problems, and solutions are expressed in the material culture of a population depend very much on cultural-traditional and social factors.

The cognitive capacity or space of an individual—and in grouping them, of a population or a species—is formed by three axes: the phylogenetic-biological axis, the ontogenetic-individual axis, and the cultural-historical axis (fig. 10; Haidle 2008a). The phylogenetic-biological axis is determined by the genetic inheritance of anatomical, neurological, and cognitive capacities of an organism and the way in which these capacities allow the perception of and interaction with the specific environment (Haidle 2008b). On the ontogenetic-individual axis, the individual potential (in its genetic and cultural limitations) of creativity, receptivity, and tolerance for new ideas is expressed and influenced by personal experiences with the specific natural and cultural environment and learning. Finally, the cultural-historical axis represents the cultural potential to accumulate, retain, and abandon traditions forwarded by cultural transmission.

The three axes of cognitive space are directly and indirectly interdependent via interactions with the specific environment formed by conspecifics, other organisms, objects, and factors of the natural and cultural surroundings relevant to the regarded species, relationships between these elements, and applicable time depth. In human evolution the phylogenetic-biological axis expanded, for example, by upright locomotion and free hands, by neuroanatomical and neurological changes in several brain areas (see Aboitiz, Aboitiz, and García 2010; Bruner 2010, both in this issue), by the expression rate of genes in the brain (Enard et al. 2002a), and by genetic mu-

tations, such as the FOXP2 gene of possible language production relevance (Enard et al. 2002*b*; Krause et al. 2007). The cultural-historical axis extended even more than the phylogenetic-biological axis. Fostered by the cultural ratchet effect—based on the understanding of others as intentionally acting beings and supported by different kinds of communication, among others, language (Tomasello 1999)—new solutions can be created by further development of older concepts and their fixation in new traditions. The ontogenetic-individual potential is markedly influenced by the life history of a species (Nowell 2010, in this issue) and thus by the development of the two other axes, by the state of the individual specific environment, and by an additional psychological moment. None of the three multifactorial axes can be examined without considering the others. The separate study of one of the three will never be able to explain the full range of the development of human cognitive space and thus modern human behavioral and cultural capacity.

The development and enhancement of working memory—its executive functions as well as the episodic buffer, phonological storage, and the visuospatial sketch pad—must have taken place within the cognitive space under the influence of all three axes in a way similar to how it must have happened for two probable facets or derivatives of working memory: object behavior and language capacity. Object behavior shows amazing structural and cognitive parallels to language. Both are built out of agents, objects, locations, and relations that are categorized and evaluated in a certain manner and linked by actions. A specific structure—or syntax—is needed to order these elements in a proper way to receive a desired result. Modern language capacity comprises a complete flexibility to rearrange the elements, according to the syntax, in infinite old and new combinations, thus enabling creativity (Reuland 2010, in this issue). Modern object behavior capacity with a modular and hierarchical organization of operational sequences allows the same for problem-solution concepts. Language generally possesses a future and past perspectives, similar to what may be deduced for quite early hominin object behavior. Both can be used as metatools: in handling artifacts (such as stories), humans are able to speculate on the thinking that may have guided the artifacts' manufacture and original purpose and are able to think about possible improvements in the tools and adaptations to other problem contexts. Thus, tools can not only be used mechanically but also can serve as cognitive instruments in metareflections—in past and future directions. Even a recursive aspect, which is considered crucial for modern language, can be found in object behavior, from a simple tool to crack open a nut to satisfy the individual's hunger to complex effective chains, as they can be seen in figures 8 and 9, with several recursive levels.

Based on these observations, I assume a gradual course of language evolution, at least partially similar to that of object behavior and comparable with the way proposed by the usage-based theory for ontogenetic language acquisition (Tomasello 2003). Language and object behavior are somehow closely

intertwined with working memory. They might have (partially) coevolved as separate aspects, or they might have developed by consecutive evolution as dependent or independent derivatives. Exaptations, subsequent functional shifts of genetically based structures to contexts other than those in which they developed (Gould and Vrba 1982), are evolutionary processes likely to have linked the development of working memory, object behavior, and language capacity on several levels. According to Wynn and Coolidge (2006), the role of language in the development of modern cultural and cognitive capacity was unquestionably an important—yet probably not exceptional—one.

## Conclusion

The examination of the problem-solution distance in animal and archaeological object behavior offers a good opportunity to study the development of several cognitive aspects that are considered to be part of working memory: executive functions including attention, active inhibition, planning, decision making, sequencing, temporal tagging, and flexibility attributed to the panmodal controlling device; the integration of information from the long-term memory in operational sequences; the comparing and contrasting of multiple sources of information (episodic buffer); the processing of information about objects and locations (visuospatial sketch pad); and the rehearsal of information, be it vocally, subvocally, or in another potential form (phonological storage). Although only a few examples have been shown here, some differences and cognitive expansions of animal species and the course of human evolution could be pointed out.

A great leap forward can be seen in the modular organization of the operational sequence evident in late Lower Paleolithic spears. The hierarchical management of parts of operational processes, phases, and single-action steps allows a simplification of the thought process and, as a consequence, an operation with more complex problem-solution units, such as composite tools. The decoupling of specific problems, tools, and solutions opens access to a broad spectrum of new combinations of known elements, as well as of new problem-solution concepts, as probably expressed in the use of mineral pigments, personal ornaments, art, musical instruments, and ritual burials. Archaeological data, however, yield information only about the preserved and discovered material manifestations of cognitive capacities. Thus, it can only roughly approach the time of the development of the basic cognitive potential.

The evolution of the cognitive capacity/space of *Homo* is influenced by three multifactorial axes: a phylogenetic-biological one, an ontogenetic-individual one, and a cultural-historical one. To single out one factor, such as a specific genetic mutation for a specific cognitive manifestation, generates causal models that appear far too simplistic. As expressions of this cognitive space, the development of working memory, object behavior, and language is determined by ge-

netic and cultural factors in a specific environment, probably to a large extent in a corresponding way and only partially different. Finally, it must be kept in mind that declarations of behavioral or cognitive uniqueness should be offered cautiously. Such stunning discoveries as the spears from Schöningen or savannah chimpanzees using sticks to hunt bush babies (Pruetz and Bertolani 2007) or to dig up underground storage organs of plants (Hernandez-Aguilar, Moore, and Pickering 2007) come to light every day.

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# Modernity, Enhanced Working Memory, and the Middle to Upper Paleolithic Record in the Levant

by Anna Belfer-Cohen and Erella Hovers

The Eurocentric (or rather Western European) outlook on cultural evolution envisioned a sharp demarcation between the phenomena grouped under the title *Middle Paleolithic* (i.e., archaic) and the phenomena recognized as *Upper Paleolithic* (i.e., modern). This view became the framework for testing cognitive, social, and economic hypotheses explaining the emergence of modern behavior. After nearly a century of research, it seems that this categorization is not applicable in the Levant despite some broad similarities between the two regions. The Levantine archaeological record provides us with the option to think outside the “European box” with regard to this important phase in human cultural evolution.

At the foundation of any discussion pertaining to “modern thinking” is the question of how one defines “modernity” in general, as well as its various derivatives. A perusal of the literature reveals that modernity means different things to different people in different disciplines. It appears there is no overarching theory within which one can address modernity issues and notions of modern thinking (see discussions in Henshilwood and Marean 2003; Wadley 2001 and references therein; Wynn and Coolidge 2010, in this issue). It follows that hypotheses constructed to evaluate modern behavior and their test implications—that is, the various criteria that people use to identify modernity—are numerous and diverse. Our discussion is no exception. We take it as a given that most of the following discourse fits only to a degree the modernity notions of other researchers. In this regard, we look to Darwin (1859), who circumvented the thorny issue of the concept of species by stating that while he was aware that the definition of the term “species” varied, there was an overall, implicit understanding of what one alludes to by it.

Indeed, such problematics are apparent in archaeological approaches to the abstract notion of “modern behavior.” Modernity has been described in various ways: symbolic behavior (including language), gendered division of labor, managed foraging, material innovation, and so on. Lately, it was argued that most if not all of these are based on the emergence of *enhanced working memory* (Coolidge and Wynn 2001, 2005; Wynn and Coolidge 2003, 2006). It is no wonder that “con-

necting cognitive theories (arising from the observed capabilities of individuals deprived of material support) with archaeological data” (Beaman 2010:S27, in this issue) is indeed rough sailing.

Notwithstanding that the staple of archaeology is material culture, interpretations of the archaeological record are anchored in the integration of input from other disciplines. This integrative nature of archaeological work has obvious strengths but also some inherent weaknesses. A common phenomenon is a discussion set in a certain theoretical framework, with the archaeological data handpicked to fit the “logic” or “common sense” of the theoretical stands on the issues in question. Such data may consist of highly visible, highly publicized records, or they are limited to the empirical “backyard” of the particular researcher.

Another disturbing symptom apparent in the literature is the endeavors to tie in biological taxonomies with cultural evidence and use data from one discipline to test hypotheses related to the other (Hovers 2006; Kuhn and Hovers 2006). As the demarcation in Europe between the Middle Paleolithic and the Upper Paleolithic seemed to overlap with the demise of the Neanderthals and the appearance of modern humans (for a recent summary of this position, see Mellars 2005), biological characteristics and cultural manifestations were rather uncritically perceived as synonymous with each other. Almost by definition, *modern behavior* has been ascribed to modern humans, whereas its existence in archaic populations (e.g., Neanderthals) requires rigorous proof (see, e.g., Belfer-Cohen and Hovers 1992; Roebroeks and Corbey 2001). This research agenda implied that only the archaeological record of archaic populations should be put on trial. It is no wonder

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**Anna Belfer-Cohen** and **Erella Hovers** are Professors at the Institute of Archaeology, Hebrew University of Jerusalem (Mt. Scopus 91905, Israel [belferac@mssc.huji.ac.il]).

that for quite a long time, Neanderthals were denied “modern” cognitive capacities.

In the following essay, we shall endeavor to evaluate the current hypotheses concerning the relationship between enhanced working memory, modern behavior, and archaeological data, bearing in mind the caveats mentioned above. While we, too, rely on data from our own Near Eastern “backyard,” we shall consider its ramifications against the backdrop of the archaeological record utilized in the formulation of those hypotheses.

Wynn and Coolidge (2010) rightly argue that persuasive cognitive archaeological arguments rest on three components: the cognitive ability under investigation must be one recognized or defined by cognitive science and must be *required* for the activities reconstructed from the archaeological traces, application of theory to archaeologically reconstructed activities requires the use of middle-range (bridging) arguments, and the essential argument required for almost all archaeologically based reasoning is that the material record under discussion be formed only by the reconstructed activities (i.e., one must be confident of the link between archaeological signature and reconstructed activity). We concur with this statement and bear it in mind while focusing our discussion on the intricacies of the pertinent Levantine archaeological record.

Even though paleoanthropological sciences are in the process of a paradigm change (as defined by Kuhn [1970]) regarding the question of modern behavior (Hovers and Kuhn 2006), the yardstick for recognizing modernity is often the criteria that had been formulated within the Eurocentric paradigm. Those can be characterized as of a presence/absence nature. Thus, there is the notion that a technological *revolution*, once considered to occur across the Middle/Upper Paleolithic boundary in Europe, took place within the African late Middle Stone Age (MSA; Mellars 2006), possibly as a result of as yet unspecified genetic changes that led to enhanced cognitive abilities (e.g., Klein 2000). Alternatively, there are advocates of a gradual change from archaic to modern behavior as a process that took place in Africa during the Middle/Upper Paleolithic, with resultant behaviors only later spreading throughout the Old World (McBrearty 2007; McBrearty and Brooks 2000). It is also possible that the behavioral changes dispersed in a mosaic fashion rather than as a package and while to some region they arrived fully set, in other instances they trickled in as isolated components. Still, the supporters of all these positions rely on the same presence/absence criteria.

The intensely researched Levantine archaeological record has never neatly fit hypotheses arguing for a revolutionary change from the Middle to the Upper Paleolithic. Moreover, the Levantine Middle Paleolithic record (ca. 250,000–50,000 years ago) has been a prime mover in changing anthropological thinking vis à vis the evolutionary relationship between Neanderthals and modern humans, also negating the assumed ties between cultural and biological affinities (Hovers 1997,

2006; Kuhn and Hovers 2006; Lieberman and Bar-Yosef 2005). At the same time, it has furnished evidence that at least some of the criteria for modernity can be met within the Levantine Middle Paleolithic record. The implication of these data is that enhanced working memory as perceived by Coolidge and Wynn (2001) not only existed before the Upper Paleolithic (beginning ca. 45,000 years ago) but also was part of the neurological wiring of Middle Paleolithic modern humans and Neanderthals alike.

## Facts of the Archaeological Record

### *Lithics*

Because lithics constitute the bulk of the material remains, it is not surprising that quite a few lithic characteristics are enumerated among the modernity criteria (e.g., the appearance of blade technology, the diversity of artifact types and technological practices, the variability of raw material). The following discussion will focus on the issue of lithics as a criterion of modern thinking, although others have proposed additional criteria such as symbolism (e.g., Henshilwood, d’Errico, and Watts 2009), executive functions (Coolidge and Wynn 2001), and age and gender divisions of economic labor (Kuhn and Stiner 2006).

*Morphological blades* (as defined by Bar-Yosef and Kuhn 1999) have occurred in the Levantine lithic repertoire since the Lower Paleolithic. *Technological blades*—that is, elongated blanks produced by specific technological practices—are known from at least the late Lower Paleolithic entity, the Acheulo-Yabrudian (Barkai, Gopher, and Shimelmitz 2005; Garrod 1956), and the early Middle Paleolithic “Tabun D” industries (Ashkenazi 2005; Meignen 2000; Monigal 2001). While they differ in technological details from Upper Paleolithic laminar reduction sequences, such early blade technologies attest to preplanning and technical adroitness. Moreover, the blade technologies of the Lower Paleolithic and early Middle Paleolithic were actually replaced by flake-dominated industries, which lasted for at least 100,000 years. In fact, such observations were instrumental in removing blade production as such from the list of modernity criteria (see discussion below).

Middle Paleolithic groups across the Eurasian landscape commonly used Levallois flaking technologies coupled with a relatively limited number of tool morphologies. This contrasts with the diverse technological adaptations of extant hunter-gatherer groups in comparably variable environments (Kuhn 1995). The latter use extractive (hunting) tool kits, notably responsive in their designs to variations in the properties of targeted prey species (e.g., Oswalt 1976). Thus, typological diversity came to epitomize the difference between modern and archaic humans in the realm of lithic artifacts.

Indeed, the Levantine Mousterian lithic assemblages are usually lightly retouched and typologically monotonous (some exceptions do occur—notably, the standardized and

design-invested Abu Sif points in the earlier Mousterian, as summarized by Goren-Inbar and Belfer-Cohen [1998]). Interestingly, it is the Abu Sif points that apparently were not used as hunting weapons (Shea, Davis, and Brown 2001). Broadly speaking, Levantine Mousterian groups opted for “maintainable” rather than “reliable” technologies (in the sense of Bleed 1986). Reliable systems are made so that they can be counted on to work when needed. Maintainable ones can easily be made to function if the lithic components are broken or if they are not appropriate to the task at hand. According to both ethnographic records and archaeological reconstructions (when available), humans tend to apply the one lithic strategy that fits their particular environment. Thus, the adoption of one strategy or the other (and the resultant lithic products) may have had less to do with modern versus nonmodern cognitive capacities and more with particular environmental circumstances. Coolidge and Wynn (2001) suggested that reliable technologies *sensu lato* may require many of the features of fully modern executive functions such as response inhibition and extensive future-oriented planning. Yet the archaeological evidence indicates that toward the end of the Upper Paleolithic (starting ca. 23,000 years ago) up to the Neolithic (broadly 10,000 years ago), maintainable rather than reliable technologies dominated the lithic tool kits in the Levant (Belfer-Cohen and Goring-Morris 2002*b*).

Hafting of lithic artifacts is positively documented in the Levant in the late Middle Paleolithic, at ca. 60,000–50,000 years ago at Umm el-Tlel (Boëda, Connan, and Muhesen 1998) and Quneitra (Friedman et al. 1994–1995). The hafting materials and techniques differ from those reported from Still Bay and Howiesons Poort contexts in South Africa starting 70,000 years ago (Lombard 2007; Wadley 2010, in this issue). Similarly, there are studies suggesting that hafting of specific tool classes took place in Europe during the Middle Paleolithic (Anderson-Gerfaud and Helmer 1987; Beyries 1987). Even if Levantine Middle Paleolithic hafting technologies first emerged in the sub-Saharan MSA contexts, their presence in the Levant may serve as an example of differential expansion rates of distinct technological innovations rather than comprehensive behavioral packages.

Despite their typological uniformity, Levantine Middle Paleolithic assemblages show much variation in their technical repertoires (Goren-Inbar and Belfer-Cohen 1998). This is evident when Levallois and/or non-Levallois technological flaking concepts were applied. The diversity of technical solutions used by hominins is not so much in the application of flaking systems (which admittedly are restricted in number) but in nuances of such flaking (dare we say technological style?), for example, in the spatial organization of core surfaces or the shaping of striking platforms (Goren-Inbar and Belfer-Cohen 1998; Hovers 1997, 1998; Meignen 1995). Such variability is observed through the Middle Paleolithic time span and across contemporaneous assemblages but not necessarily as a gradual, linear trend. Because the changes are clearly not incremental or directional toward an Upper Paleolithic “deadline,”

the Middle Paleolithic too often comes through as a period of lithic stasis (Hovers 1997; Kuhn and Hovers 2006).

At the same time, the variability seen in the Levantine Middle Paleolithic record is likely a key point in explaining the acceptance of new technological features at the onset of the local Upper Paleolithic, which initially and for quite a while retained some technological concepts of the Middle Paleolithic (Hovers 1998; Hovers 2005, cited in Belfer-Cohen and Goring-Morris 2007:199; Meignen and Bar-Yosef 2002). Most obviously, the Levantine Mousterian notion of a pre-planned, prepared core technology actually continues into the Upper Paleolithic (Belfer-Cohen and Goring-Morris 2007, 2009). The Ahmarian (i.e., the first full-fledged Upper Paleolithic entity in the Levant) is characterized, among other things, by narrow-fronted (N-fronted) cores (Davidzon and Goring-Morris 2003; Goring-Morris and Davidzon 2006). Rather than a brand-new technological concept, these represent a technological shift from a Middle Paleolithic “surficial” approach to core reduction to a “volumetric” one. This process differs from the more radical change often depicted in Europe (e.g., Boëda 1990). Levallois points in the Levant are replaced by projectile elements displaying subtle yet profound changes in the specifics of blank production and platform preparation. Nevertheless, the intermediate form, the Emireh point, probably provides some indication as to the logic involved in this shift because it is typified by basal thinning, most probably to facilitate hafting (Belfer-Cohen and Goring-Morris 2009). This bifacial thinning was rapidly replaced by abrasion of the removal surface of N-fronted cores, thus enabling more efficient exploitation of the initial volume of the nodule. A low-key innovation in and of itself, it nonetheless led to related improvements, such as the production of more functional blanks per unit volume. This innovation can actually be described as a conceptual refinement of the Levallois “recurrent” approach (Davidzon and Goring-Morris 2003). Accordingly, early Upper Paleolithic technology can and should be viewed more in terms of modifications of the underlying concepts associated with Middle Paleolithic technologies rather than revolutionary conceptual changes (Belfer-Cohen and Goring-Morris 2002*a*, 2009; Davidzon and Goring-Morris 2003; Goring-Morris and Davidzon 2006).

The Levantine Middle Paleolithic record also offers glimpses into symbolic realms, which most paleoanthropologists accept as a reliable sign of modernity (e.g., Barham 2007). These comprise burials, pigments, personal ornaments, and engravings, all of which are typically associated with the Upper Paleolithic and accepted as depicting modern behavior (McBrearty and Brooks 2000). Wynn and Coolidge (2007:85) caution that the archaeological record of these behaviors is not sufficiently clear as to how they are related to modern thinking, consonant with their proposal of “enhanced working memory.” These authors argue that the concept of symbolism, particularly within the discipline of anthropology, is too often uncritically examined and underdeveloped. Hence, this evidence may not automatically constitute proof of cog-



nitive modernity. Nonetheless, we posit that the various material manifestations of a symbolic nature portray behaviors requiring the mental capacities for abstract thinking, generalization, intentionality, and mental plasticity, which are considered the hallmarks of enhanced working memory.

### Burials

Middle Paleolithic intentional burials are found in Europe (associated with Neanderthals) and in the Levant (associated with both Neanderthals and anatomically modern *Homo sapiens* [AMHS]; Bar-Yosef et al. 1992; Belfer-Cohen and Hovers 1992; Defleur 1993; Hovers, Kimbel, and Rak 2000; Hovers et al. 1995; Tillier 1990). Moreover, some of the burials incorporate grave goods, such as red deer antlers on the chest of a child (Qafzeh 11; Vandermeersch 1970), a boar mandible held by a male (Skhul V; McCown 1937), and a red deer mandible with an infant (Amud 7; Rak, Kimbel, and Hovers 1994). It is intriguing to observe that there are no burials (as defined by Belfer-Cohen and Hovers [1992]) associated with the MSA (Hovers and Belfer-Cohen, forthcoming). By the criteria applied to the Eurasian Middle Paleolithic record, the Herto skulls do not appear to represent burials. The cut marks on some of these specimens (Clark et al. 2003) possibly represent a different symbolic behavior associated with mortuary practices. Once again, the archaeological evidence refutes the validity of a comprehensive modern-behavior package, repeatedly stated to be the hallmark of the new era of modern humans (Klein 1995, 2000; Mellars 2005; Mithen 1996).

### Pigments

The use of pigments, whether in mundane or symbolic contexts, appears both during and after the Middle Paleolithic. Thus, it cannot serve as an indication for the appearance of novel behaviors during the transition. There are variable interpretations of the use of hematitic ochre in the MSA. While some argue for its exclusively symbolic use (e.g., Barham 2002, 2007; Watts 1999, 2002), others point out that it is related to hafting, suggesting that the symbolic meaning, if present, is of secondary nature (Lombard 2007; Wadley 2005a, 2005b, 2010). While there is strong evidence for hafting in the Levantine Middle Paleolithic, it does not involve the use of ochre (Boëda, Connan, and Muhesen 1998; Friedman et al. 1994–1995). The infrequent occurrence of red pigments bears a strong symbolic signature (Hovers et al. 2003; see below). Conversely, the elevated quantities of ochre in Upper Paleolithic sites are probably associated mainly with mundane, functional contexts (e.g., hafting procedures; Belfer-Cohen and Goring-Morris 2002b).

### Beads and Incised Pieces

The context and nature of the sporadic occurrences of beads in both the Middle Paleolithic Levant and the MSA (Bar-Yosef and Vandermeersch 1993; Bar-Yosef Mayer 2005; Bouzouggar

et al. 2007; d'Errico et al. 2005; Taborin 2003; Vanhaeren et al. 2006) “indicate that the choice, transport, coloring, and long-term wearing of these items were part of a deliberate, shared, and transmitted nonutilitarian behavior” (Bouzouggar et al. 2007:9969). If beads are accepted as a form of “information technology” on an intergroup scale (Kuhn and Stiner 2007, following Wobst 1977), we once again have evidence for efficient problem-solving devices associated with working memory in the Middle Paleolithic as early as 120,000 years ago (Bouzouggar et al. 2007; Vanhaeren et al. 2006). Even though Middle Paleolithic shell beads are associated with the remains of AMHS, they occur in rather low quantities in the Levantine early Upper Paleolithic, and their increase through time is gradual rather than dramatic (Bar-Yosef Mayer 2005). Clearly, this situation is inconsistent with a scenario of revolutionary increase in symbolizing capacities of a specific biological taxon or with notions of dramatic increase in intergroup information networks. The few incised items (including lumps of ochre; Goren-Inbar 1990; Henshilwood et al. 2002; Hovers, Vandermeersch, and Bar-Yosef 1997; Hovers et al. 2003; Marshack 1996) may be also considered as symbolic, information-encoding devices, although possibly on a smaller spatial scale (Wobst 1977). Heeding Wynn and Coolidge's (2010) formalization of the three components for a valid cognitive archaeological argument, we posit that symbolic explanations are the parsimonious scenarios explaining such phenomena (e.g., Bar-Yosef Mayer, Vandermeersch, and Bar-Yosef 2009; d'Errico et al. 2005; Hovers, Vandermeersch, and Bar-Yosef 1997, 2003).

## Discussion

The fact is, I think, that to get an idea across it has to be exaggerated, lifted out of the confusion and multiplicity of real life and placed on an intellectual pedestal. It has to pretend autonomy and omniscience so as to goad others to challenge. (Wilson 1988:2)

The concept of modernity, defined through a package of characteristics that served as the measuring stick to test the existence of modern behavior in the archaeological record, is an example of the above quotation. With time, the broad and sweeping strokes by which researchers painted the prehistoric picture of the Middle and Upper Paleolithic periods were replaced with more subtle, detailed brush touches. It became painfully clear that there are difficulties in tying the archaeological record to cognitive theories, given that paleoanthropologists infer abstract capacities—that is, language, symbolic thinking, strategizing, and planning complex actions—from material remains.

The archaeological record of Australia, first settled in the mid-Upper Pleistocene by modern humans (Hudjashov et al. 2007; O'Connell and Allen 2004), illustrates this point. While some of the criteria used to identify modernity are missing, especially those related to the lithic component of the material

culture, there is ample evidence for the presence of other “diagnostic” markers of modernity, as, for example, shell beads, ochre, grinding stones, and hafting (Lourandos 1997). Apparently, in Australia, diversity of stone tool morphology or innovations in tool production and stone tool use technologies do not necessarily go hand in hand with other aspects of modern behavior.

Indeed, modernity is multifaceted and cannot be confined to a rigid set of present/absent characteristics. If anything, the Australian record teaches us that the modernity phenomenon is of a mosaic rather than a monolithic nature. Our overview demonstrates that this is true of contemporaneous as well as earlier records in Eurasia and Africa. Moreover, this is true of hominins other than *Homo sapiens*. Certainly by virtue of their membership in the hominin lineage and their long evolutionary history, archaic humans most probably displayed individual variability similar to the variability one can observe in present-day humanity (Engle 2010).

Wynn and Coolidge (2007:88) have recently suggested that a piecemeal approach is required to understand the evolution of enhanced working memory and the modern mind. The same approach should be applied, and even more forcefully so, to the study and understanding of the archaeological record. Bearing this in mind, our review of the Middle and Upper Paleolithic record of the Levant clearly illustrates that (a) enhanced working memory and its implications concerning the modern mind had emerged quite a while before the Middle to Upper Paleolithic transition (for a similar statement regarding the central African record, see Barham 2007:173); (b) the actual data portraying the existence of enhanced working memory appear on and off all through the Middle Paleolithic record, and conversely, some “markers” of modern behavior (e.g., burials) are not known from most of the Levantine Upper Paleolithic period; and (c) modern anatomy (AMHS) and behavioral modernity are clearly separate issues (Hovers 2006; Kuhn and Hovers 2006; Lieberman and Bar-Yosef 2005) that do not emerge in tandem by default.

Here we draw a lesson from the history of primate research. Initially, researchers looked for evidence of behaviors that separated apes from humans. This entailed active searching for the limits and boundaries of the ape behavioral repertoire. Yet under laboratory conditions, apes were able to exhibit behaviors that had never been observed in the wild and were traditionally assumed to be human prerogatives. In turn, these findings opened new research frontiers, raising the questions of why and how apes acquired such elaborate mental capacities. To wit, researchers were faced with the need to first identify and then understand the evolutionary processes that led to costly yet seemingly unexploited abilities. This turn of events gave rise to explanatory models, such as “Machiavellian intelligence,” that posit the crucial role of social skills and relations in the development of cognitive capacities (Humphrey 1976; also see Aiello and Dunbar 1993; Dunbar 2003; but see Byrne and Bates 2007). For example, these new data indicate that elements of theory of mind are part of the cog-

nitive makeup of nonhuman primates (e.g., Roth and Dicke 2005).

The analogy herewith is as follows: We argue that modern cognitive abilities to store information existed a long time before they became a regular/normative phenomenon of the archaeological record (see Chase 2006). What should become the focal point of discussion are explanatory models for their *erratic* appearances and reappearances through time and space (Hovers and Belfer-Cohen 2006). We have to explore the circumstances and contexts in which the phenotypic expressions of the capacities for innovation and problem solving became *fixed* features of human societies, so much so that they are perceived as synonyms of modernity (Coolidge and Wynn 2001, 2005).

Some of the explanations that appear in the literature concerning inventions becoming innovations (for the distinction between the two, see Renfrew 1978) refer to subsistence needs associated with differences in the environment. Supposedly, these in turn either suppressed or stimulated innovations that appear on the “checklist” of behavioral modernity (Henshilwood and Marean 2003). The idea in its broader sense has been accepted by many researchers, yet interestingly enough it led to different and sometimes contrasting interpretations. In essence, the issue was whether “necessity is the mother of invention” or, in our case, of innovation.

According to some, hunter-gatherers in the tropics were under less pressure to develop specialized technologies than their high-latitude counterparts, who had to deal with more seasonal variability of subsistence resources (Henshilwood and Marean 2003). Other researchers hold a radically opposed position, suggesting that the affluence and variability of subsistence resources in low-latitude ecosystems drove hunter-gatherers to maximize their returns from the environment by technological and social innovations (Kuhn and Stiner 2006).

It seems that the impetus for a human group to accept and implement inventions is multifaceted and anchored in different, interlinked realms of existence. It appears that social and demographic factors are as crucial as subsistence resources or genetic determinants. It is actually impossible to separate all of these into clear-cut, discrete domains. Ethnographic studies amply illustrate intricate correlations between resource availability and diversity and demographic structure and symbolic expressions (see the work of Barham [2007], integrating the works of Douglas [1970] and Foley [2004], among others).

Indeed, we believe that inventiveness per se is part of primate cognition in general and of humans in particular. Thus, it seems that the visibility and frequencies of the so-called modern features in the archaeological record reflect not only the internal mental capacities involved but also, or even mainly, the external circumstances in any specific instance. It is only under favorable conditions that social groups can afford to check out those inventions and select and retain the advantageous ones.

Like the behaviors of extant humans, those that we observe

in the archaeological material record reflect actualization of societal knowledge. We believe that their occurrences indicate that in each case they persisted long enough to be archaeologically visible. The retention and transmission of those behaviors has been essentially dependent on cultural mechanisms (e.g., rites, myths, social identity). These in turn depend on both external and internal circumstances (Hovers and Belfer-Cohen 2006). Among those, demographic conditions are fundamental for the continuous transmission of knowledge (Shennan 2001). On a geographical scale, low-density, sparsely distributed populations would have left only ephemeral material signatures of symbolically organized behaviors (Barham 2007:172). Over time, continuous low population densities in any given region would have disrupted the networks of exchange and transmission, leading to the disappearance of evidence for the pertinent cultural mechanisms from the archaeological record. The “nonmodern” nature of much of the archaeological record of the Middle and Upper Paleolithic Levant can be explained in light of such a scenario. In this context, it is of interest to mention the Flynn effect, that is, the rise of average intelligence quotient test scores over generations. Among the explanations of this trend, we find improved nutrition, a tendency toward smaller families, better education, greater environmental complexity, “hybridization vigor,” and reduced inbreeding. Apparently, heredity per se is but one factor among many influencing this cognitive phenomenon (Flynn 2007; Mingroni 2007).

Undoubtedly, the neural basis for working memory and enhanced working memory had to appear at some point in human evolution. As archaeologists, we have less to contribute to the question of *why* this may have happened (see Aboitiz, Aboitiz, and García 2010; Bruner 2010; Engle 2010, and others in this issue). Yet we are well positioned to comment on the time frame during which it happened in the Levant. Accordingly, we believe that enhanced working memory occurred earlier than the Middle to Upper Paleolithic transition, although it became a staple of the archaeological record only in the advanced stages of the Upper Paleolithic. From the Levantine viewpoint, a gainful venue for future research will not focus on *why*, *where*, or even *when* enhanced working memory emerged. Instead, we should look at the mechanisms that dictated the waning and waxing nature of its appearance in the archaeological record. Modern thinking is only partly an evolutionary issue; it was shaped and modified mostly by historical circumstances (Boyd and Richerson 1992) that made “modernity” the hallmark of modern humans.

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# The Colonization of Australia and Its Adjacent Islands and the Evolution of Modern Cognition

by Iain Davidson

The first colonization of the Greater Australian continent, known as Sahul, indicated that humans had modern cognitive ability. Such modern human abilities probably emerged earlier in Africa. I will argue that the only way we can identify what constitutes modern human behavior is to look at the record in Australia—the first place colonized only by modern humans. I place this argument within recent theorizing about cognitive evolution.

## Australia and the Evidence for Modern Human Cognitive Ability

One view of the evolution of human behavior and cognition depends on an argument that the evolutionary emergence of language occurred late in hominin evolution. While Wynn and Coolidge (2010, in this issue) are right that some arguments about the importance of language have not been thoroughly warranted, others have been expansive and careful to spell out the relationship between language and modernity (e.g., Noble and Davidson 1996; Nowell 2001). This view suggests that human cognition is fundamentally different from that of other hominins because we humans use language and other hominins did not (but for further views, see Barnard 2010*a*, 2010*b*, in this issue; Davidson 2010*a*). An argument of this sort suggests that the important selective context was found in social processes rather than just neural events (Davidson and Noble 1989; Noble and Davidson 1996). Noble and I have argued that language use is the distinctive feature of modern human behavior<sup>1</sup>—now and in the past—characterized by increased information flow, greater planning depth, and the capacity for conceptualization that we humans take for granted (Noble and Davidson 1991). Previously, I argued that the evidence from stone tools was more difficult to interpret than the standard story would have it (Davidson and Noble 1993). In searching for more distinctive archaeological evidence for the emergence of these characteristics, the development of watercraft for the first colonization of Australia seems to be a clear-cut example of modern human behavior. In the terms defined by Wynn and Coolidge (2010),

the watercraft represents a facility that indicates “long-range temporal planning” (S11) and probably involved “active maintenance of appropriate stimulus representations relevant to goal attainment in the face of interference-rich contexts” (S8) at more than one level. On this basis, we argued that the peopling of Australia provides the earliest certain evidence for the use of language (Davidson and Noble 1992); now we might claim that it represents evidence for modern thinking.

In this paper I go further and try to avoid the difficulty entailed in most studies of the emergence of modern human behavior that results from the fact that Africa, Europe, and Asia were occupied first by nonmodern hominins and then by modern humans. Deciphering the signature of modern human behavior is made more difficult by deriving arguments from our knowledge of these mixed records. Here I suggest that we need to give priority to the Australian evidence if we want clarity about this key process in human evolution. In doing so, I will put the argument into the terms of my understanding of working memory with some reference to Barnard’s development of interacting cognitive systems (Barnard 2010*b*; Barnard et al. 2007).

Discussions of the emergence of modern human behavior can tend to circularity because of the history of archaeological studies and the priority of Western Europe in the construction

1. When Noble and I first used this term in the title of our 1991 paper (Noble and Davidson 1991), we sought to show what were the characteristics of such behavior as a novelty in human evolution. Clearly, there are many uncertainties in the use of the term “modern,” because it is applied equally to the modernity that emerged at the time of the Renaissance in Europe, to a movement in art and architecture in the early twentieth century, and to the process of “modernization” of societies that in other contexts might be described by euphemisms such as “developing.” In this paper I am concerned with the meaning that Noble and I sought to define in 1991, which coincides with “modern thinking” as used by Coolidge and Wynn (2009).

**Iain Davidson** is Emeritus Professor of Archaeology in the School of Humanities, University of New England (Armidale, New South Wales, Australia [iain.davidson@live.com.au]).

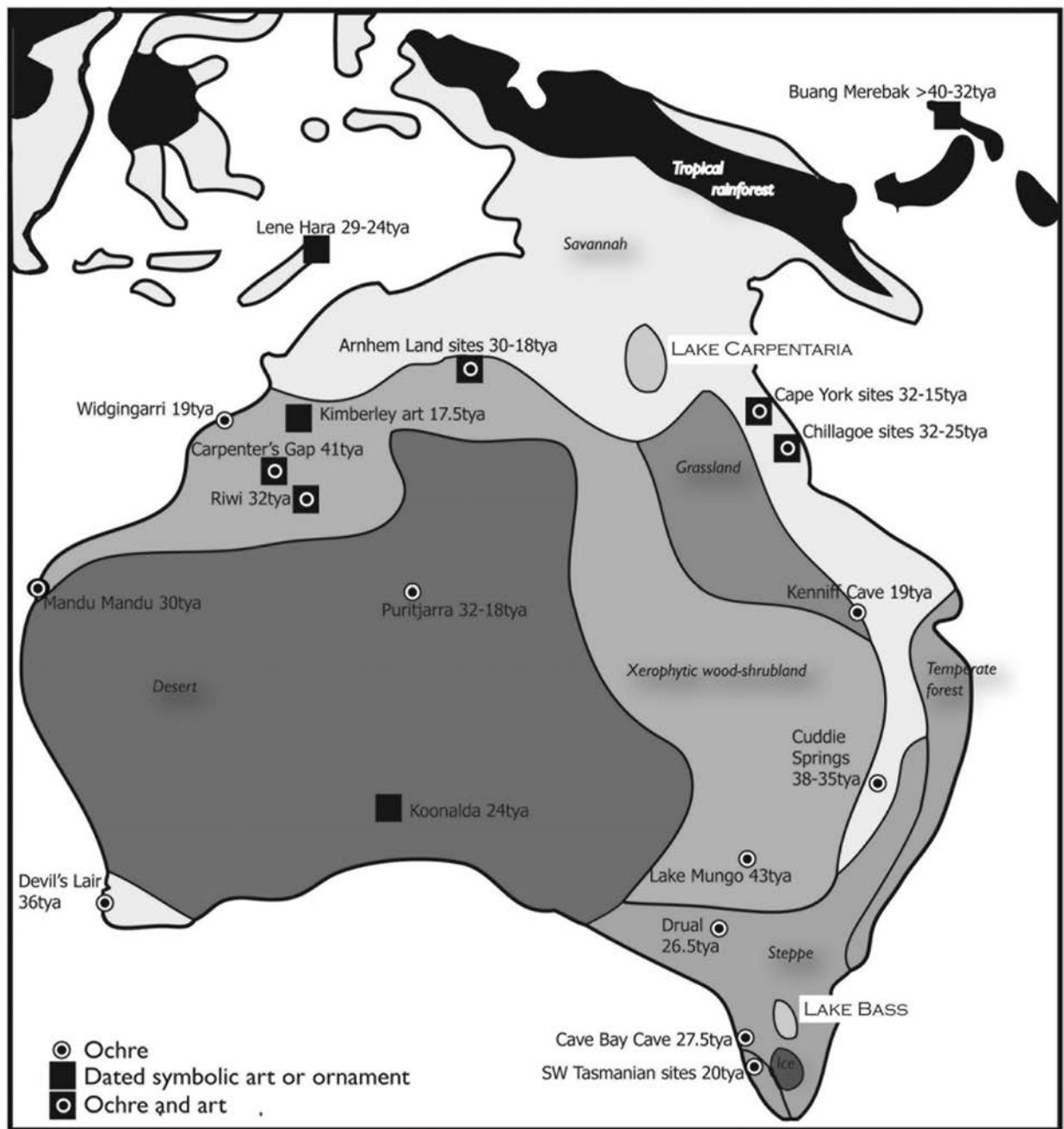


Figure 1. Dates for art and ochre at sites in Sahul and Timor (see Habgood and Franklin 2008) showing vegetation zones and landmasses reconstructed for the Last Glacial Maximum by Hope et al. (2004). A color version of this figure appears in the online edition of *Current Anthropology*.

of the story of deep prehistory. There have been two principal approaches to the emergence of modern human behavior. The oldest is based on the assumption that the European Upper Paleolithic, particularly through its rich cave art (e.g., Clottes 2001), marked the beginning of modern human behavior (e.g., Duff, Clark, and Chadderton 1992)—an ap-

proach that is still lingering despite overwhelming evidence to the contrary (Davidson 1997). As Belfer-Cohen and Hovers (2010, in this issue) characterize it, a large part of this argument derived from the apparent need to explain the replacement of Neanderthals (in Europe) by modern humans. This argument has tended to use a trait-list approach, taking



characteristics of the Upper Paleolithic as indicators of modern human behavior and considering the evidence for the appearance of such traits in various archaeological records (e.g., McBrearty and Brooks 2000), including, as Belfer-Cohen and Hovers show, among those of Neanderthals. This approach also tends to circularity because it is not always clear why a particular set of archaeological evidence should be classified as Middle or Upper Paleolithic, as the historic arguments about the French Châtelperronian industry showed. The second approach, that Noble and I (Noble and Davidson 1991) attempted, defines the theoretical reasons why we should identify particular behaviors as modern. Working out appropriate methodology, we can then link the theoretical argument with the archaeological data. But even those attempts have some circularity insofar as our argument began from the same contrast in the European archaeological record (even though it moved away from it quite quickly) rather than defining modern human behavior from the behavior of humans only in the present day.

A third way would produce an empirical generalization about the behavior associated with the earliest skeletal remains that can be called modern human, but until recently there has been little enthusiasm for that approach (but see, e.g., Henshilwood and Marean 2003). The difficulty here is that there may be no immediate match between the appearance of modern human skeletal form in Africa and associated behavioral change, although the discovery of marine food getting, ochre use, and stone bladelet production at Pinnacle Point in South Africa might be interpreted as taking some of the behavioral features back to ~164 tya,<sup>2</sup> that is, to dates approximating the earliest appearance of modern human skeletal form (Marean et al. 2007). This approach would get over the problematic “erratic appearances and reappearances” question that arises from trying to match modern data with the original problem from which the question of modernity was imperfectly defined. Currently, there may be some inhibition about this because of what Renfrew (2008) called the “sapient paradox”—the appearance that not all skeletally or genetically modern humans exhibited modern behavior. This is, of course, a fallacious paradox caused by a conceptualization of mental abilities as innate capacities generated by the same selective processes that operated on skeletons rather than as the products of distributed cognition that arise from the interactions of individual minds with others and with the material products of those behaviors.

One view of the Middle Eastern archaeological record (but see Belfer-Cohen and Hovers 2010) would have it that the earliest modern humans there, as represented at sites such as Qafzeh, did not have the adaptability that later humans had

and that the early expansion of creatures with modern human skeletal form into the domain of Neanderthals was followed by the return of the Neanderthals and a retreat of the moderns (Tchernov 1998; but see Belmaker 2009). However, recent reassessment of the evidence from Neanderthal sites seems to suggest that European Neanderthals had some of the traits of modernity discussed elsewhere (d’Errico 2003). Genetic evidence seems to suggest a coalescence time between humans and Neanderthals about 700 tya with a genetic separation about 370 tya (Noonan et al. 2006). Similarities of behavior, then, need to be assessed carefully to see whether they result from a common ancestral behavior or from convergence despite the genetic separation. Do the traits found among Neanderthals that are said to mark modernity imply that modernity predates genetic separation or that these traits are a convergent result of more fundamental cognitive abilities and thus do not mark modernity at all?

In the absence of clear contrast between the behaviors of the two species in the early Middle Eastern case, it seems necessary to approach the problem from a new direction. This is the approach I adopt here, using the colonization of Australia as a limiting case. Australia was colonized by modern humans before Europe (O’Connell and Allen 2004) and before the genetic change postulated to have made the brain of modern humans fit for language (Klein 2000). All people who have ever lived in Australia have had fully modern skeletons (Brown 1997). Despite earlier claims to the contrary (Redd and Stoneking 1999), there seems to have been little admixture with new genes subsequent to initial colonization (Hudjashov et al. 2007). All Australians were fully modern in their behavior when first observed by Europeans (Davidson 2007). There are now also some examples of analysis of early archaeological evidence of behavior in terms of traits that might characterize modern human behavior (Balme et al. 2009; P. Veth, N. Stern, J. McDonald, J. Balme, and I. Davidson, unpublished manuscript; see below).

Most important, in questions of human cognition the answers can be derived only from behavioral evidence. That is how cognitive scientists work: they seek evidence of particular neural events in the context of controlled behavioral experiences (e.g., Smith and Jonides 1997). It should be the same with the evolution of cognition: the primary evidence should come from archaeological evidence for behavior rather than from skeletal remains, genetic arguments, or any other form of inference that does not rely on evidence of behavior (Davidson 2010a). But the logic of this position requires that we seek evidence known to be the result of modern human behavior in the exemplar geographic region.

The work of McBrearty and Brooks (2000) has dominated recent discussion because it produced an apparently comprehensive trait list for the identification of modern human behavior, but this seems to have been little more than an empirical generalization from interpretations of the transition in Europe without strong theoretical basis. Several of the traits they identified were discussed in our original consideration

2. All dates are given in thousand years ago (tya). I have used this unorthodox shorthand to include dates estimated from calibrations of radiocarbon dates (Weninger, Joris, and Danzeglocke 2002) and dates by methods other than radiocarbon that do not need calibration. Specialists should consult the original sources for the uncalibrated dates.

of the emergence of modern human behavior (Noble and Davidson 1991), but in addition we identified three aspects of modern human behavior that underlie all of the traits that might be used to recognize it in the archaeological record: information flow, planning depth, and conceptualization consequent on the emergence of language. McBrearty and Brooks had a similar list (but without discussion of theoretical reasons for them): abstract thinking; planning depth; behavioral, economic, and technological innovativeness; and symbolic behavior. A previous paper (Davidson 2007) considered how the theoretical cognitive features apply separately or in combination with the traits identified by McBrearty and Brooks (2000).

Noble and I did not include in our earlier discussions two traits of the technology suggested by McBrearty and Brooks. The first of these—blades, microblades, and backing—need further argument about their conventional nature to meet our criteria. Blades alone can be problematic (Davidson 2003), but the backed artifacts from Klasies River certainly have the characteristics of convention (Davidson and Noble 1993). Elsewhere (Davidson 2010a, 2010b) I have argued that the *lame à crête* method of preparing a core for blade production does indicate fully modern cognition because of the separation of this module of knapping from the production of the series of blades. The proliferation of tool categories is also a difficult trait, given the perils of overinterpretation encapsulated in the phenomenon I called the “finished artefact fallacy” (Davidson 2002). Many of the “tool” categories recognized by archaeologists may be regularities that arose from the practices of knapping (or of archaeological classification!) without any prehistoric intention to produce such forms (see, e.g., Dibble 1984; Moore 2007). As it happens, neither blades nor the proliferation of tool categories are features of the early Australian or Tasmanian material culture.

Similarly, curation of exotic materials may be due to a variety of different circumstances, and they can hardly be considered a characteristic of modern human behavior, given that there are items such as the unmodified pebble transported several kilometers to the site of Makapansgat (Bednarik 1998) from the very beginning of the hominin story. Scheduling of activities, site reoccupation, and structured use of space all also have ambiguous characteristics in the archaeological record. The sites of Olduvai Gorge (e.g., Leakey 1971) clearly indicate at least the second two and probably the first, but this is not because of the modernity of the hominin behavior. I will discuss the remaining traits in the final sections of this paper.

For the purposes of this issue, the question is whether Coolidge and Wynn’s (2009) version of enhanced working memory accounts for the emergence of modern human behavior as archaeologists have envisaged it. I will, therefore, look for evidence that the first colonists of Australia exhibited behavior that required enhanced working memory. Once we have identified what behavior that was, we will be in a better position to examine the archaeology of the rest of the world

to see when we can identify such markers and to ask the implications for understanding the evidence of behavior outside Australia and earlier than its colonization. There is, however, the continuing paradox that in order to identify the archaeological evidence of behavior that demonstrates working memory, we will tend to look at precisely those examples used in the trait-list approach. The difference is that we will be deriving our use of those (and other) behavioral cues from a theory-based argument—consistent with the behavior of present-day people—about how they are examples of modernity.

Baddeley and Logie (1999) defined working memory thus: “it comprises those functional components of cognition that allow humans to comprehend and mentally represent their immediate environment, to retain information about their immediate past experience, to support the acquisition of new knowledge, to solve problems, and to formulate, relate, and act on current goals” (28–29). The novelty of this approach was the definition of a multicomponent working memory now thought to have four subsystems: the phonological loop, the visuospatial sketch pad, the central executive, and an episodic buffer (Baddeley 2003; for a full description, see Wynn and Coolidge 2010). Baddeley’s identification of a phonological loop as an essential component of the functioning of working memory begs the question of whether nonhumans, which do not use language, could possibly have working memory as Baddeley conceived it. Others have used the model to postulate a gradualistic emergence of the neuroanatomy suitable for language (Aboitiz, Aboitiz, and García 2010, in this issue; Aboitiz and García 1997), while Barnard (2010b) shows how a more complex conceptualization of human cognition and its evolution might have generated the elements that characterized Baddeley’s model.

Some might argue that only the first criterion (“to comprehend and mentally represent their immediate environment”) seems easily restricted to humans alone. It is a quite widespread feature of some psychological theories that views of the uniqueness of human behavior can result from ignorance of animal behavior (see Laland and Hoppitt 2003). At the same time, it is difficult to identify some of these characteristics in nonhuman (living) animals because animals can give no account of their actions. Nevertheless, cleverly designed experiments have shown something like working-memory function among captive chimpanzees (Inoue and Matsuzawa 2007) and perhaps monkeys (Orlov et al. 2000; Subiaul et al. 2007), a story we might treat with caution, given that it results at least in part from the ingenuity of the experimenters. There is, nevertheless, some indication that free-ranging rhesus monkeys have similar functions (Wood et al. 2008). Reader and Laland (2002) showed through a meta-analysis of animal behavioral literature that there is a strong correlation among primates between executive brain size on the one hand and innovation and social intelligence on the other, suggesting that the degree of innovation in a species may depend on its brain size. This would have obvious im-

plications in hominin evolution, given the two separate episodes of brain size change in the hominin record (Davidson 1999b).

Some literature about the Baddeley model of working memory is concerned about the location of the neural functions associated with it in the brain (e.g., Cowan 1999). This is a problematic question for archaeologists, given the difficulty paleoneurologists have in inferring the nature of brain function from the surface structures of the cortex revealed in endocasts (e.g., Falk et al. 2005; but see Bruner 2010, in this issue). Moreover, if we are concerned about the internal functioning of brains, it seems to be a much more interesting question how particular patterns of relations between the parts may have been selected by natural selection. Presumably, a major part of the selective process was the behavior of the people whose brains made the connections of which they were capable. In seeking to understand the evolution of working memory, therefore, we might look for evidence of the behaviors that entail the sorts of ability that working memory bestows, and the best evidence of them is to be found in the archaeological record.

## The Early Archaeological Record in Australia

Balme and her coauthors (2009) have recently summarized the evidence for the peopling of the route from Africa to the new world of Australia. For the purposes of this paper, that evidence could still be ambiguous, as much of the route was previously occupied by nonmodern hominins. Here I will concentrate principally on the evidence from Australia and its adjacent islands. For most of the period of its occupation by people, Australia has been joined to New Guinea in a continent known as Sahul by the dry land exposed at the low sea levels associated with the Pleistocene ice ages (fig. 1). The same low sea levels exposed the continental shelf joining many of the islands of western Indonesia to mainland southeast Asia in a continental area known as Sunda. Sunda and Sahul were always separated by a sea filled with islands. At a minimum, eight or 10 sea crossings were always necessary for people to reach this continent from those islands to the west (Birdsell 1977), and archaeological evidence from the islands to the northeast of Sahul shows that early in the history of peopling the continent, further sea crossings were made beyond the continent into island Melanesia (Allen et al. 1988; Summerhayes and Allen 1993).

There have been several recent syntheses of the early archaeological record in Australia and its relations with modern human behavior (Balme et al. 2009; Brumm and Moore 2005; Davidson 1999a; Franklin and Habgood 2007; O'Connell and Allen 2007; Stern 2009; P. Veth, N. Stern, J. McDonald, J. Balme, and I. Davidson, unpublished manuscript). Noble and I previously considered the evidence then available that would support our argument about the cognitive abilities, particularly the ability to strategize and plan complex actions implicit

in the making of sea-crossing watercraft, personal decoration, ground ochre, other ochre, ground-bone tools, and ground-edge axes (Davidson and Noble 1992). In addition, the making of watercraft and the likely activities for which they were made strongly suggest that deepwater fishing was an important activity in the islands to the west of Sahul before 40 tya (Balme 1995).

The parsimonious interpretation of the evidence for the earliest colonization of Australia and island Melanesia (O'Connell and Allen 2004) is that the dates that are undoubted proof of a human presence are limited to the period between 44 and 50.5 tya. There are other dates between 50 and 60 tya by methods other than radiocarbon (e.g., Roberts et al. 1994; Turney et al. 2001), but O'Connell and Allen advise caution about the certainty of the association between the archaeological occupation and the dated materials. By 41 tya, people reached Tasmania (Cosgrove 1995), shortly after a landbridge opened up as sea level fell to the minimum of the Last Glacial Maximum (Lambeck and Chappell 2001). At the time, Tasmania was principally a steppeland, and by 30 tya, people were in most habitats of Sunda and Sahul and island Melanesia, with the possible exception of grassland (Balme et al. 2009), from desert (Smith et al. 2001) to tropical rain forest (Pavlidis and Gosden 1994).

The colonization of the route from Africa to Australia by modern humans was accomplished at a speed that Pope and Terrell (2008) estimate was on the order of 1 km/year for the Asia Pacific region. This appears to be more than twice the rate estimated for the colonization of Europe by modern humans (Mellars 2006), despite the fact that part of that process involved moving into new habitats far more unfamiliar than in passing from Africa to Asia to Europe. At that rate it would have taken less than 4,000 years to get from first landfall to Tasmania.

Nevertheless, moving into a new range of territories and expanding the diet breadth are two of McBrearty and Brooks's (2000) traits of modern human behavior that were found in Africa, Sunda, and Sahul and continued as far as the occupation of Tasmania (table 1). If the rate of dispersal was only because of an unprecedented demographic expansion (Powell, Shennan, and Thomas 2009), that merely shifts the question to ask what caused the demographic expansion. It is tempting to argue that the speed of this adaptation may have been due to the strategic and planning abilities and enhanced information flow made possible by the use of language. The first colonists of Europe also had language, but perhaps their progress was slowed by the occupation of the continent by Neanderthals.

Table 1 shows that several other traits of McBrearty and Brooks (2000) were also characteristic of behavior in all four of the regions: hafting and composite tools (also a feature of Neanderthal behavior; Boëda et al. 1999), discussed by Wadley (2010, in this issue); new materials for tools; special-purpose tools; greater control of fire; the use of pigments (also documented among Neanderthals; d'Errico and Soressi 2006);

Table 1. Traits of modern human behavior found in Africa (Middle Stone Age), Sunda, Australia, and Tasmania

Trait <sup>a</sup>	Cognitive class <sup>b</sup>	Africa	Sunda <sup>c</sup>	Australia <sup>d</sup>	Tasmania <sup>e</sup>
Range extension to previously unoccupied regions	2	Yes	Yes	Yes	Glacial margins (and rain forest margins?)
Increased diet breadth	1	Yes	Marine and rain forest	New fauna and flora (megafauna?)	Yes
Hafting and composite	2, 3	Yes	Watercraft	Axes, bone points	Yes
New tool materials	3	Yes	Shell	Yes	Bone points
Special-purpose tools	3	Yes	Pits for leaching?	Axes and grindstones	Baskets
Greater control of fire	2 and 3	Yes	Yes	Yes	Yes <sup>f</sup>
Use of pigment	3	Yes	Yes	Yes	Yes
Image and representation	3	?	Yes	Yes	Yes

<sup>a</sup>McBrearty and Brooks (2000).

<sup>b</sup>The cognitive class assessment is based on the theoretical aspects of modern human behavior identified by Noble and Davidson (1991): 1, information flow; 2, planning depth; 3, conceptualization. Those traits with none of the cognitive traits are omitted.

<sup>c</sup>Balme et al. (2009).

<sup>d</sup>Stern (2009).

<sup>e</sup>Davidson (2007).

<sup>f</sup>Gott (2002).

and the use of image and representation. These common traits involve the three characteristic cognitive features of information flow, planning depth, and conceptualization, sometimes separately and sometimes together. The use of image and representation can be interpreted in appropriate circumstances as showing the symbolic structuring of the relations between people and between people and their environments, which is one particularly powerful manifestation of modern human behavior (Davidson 1997, 2005, 2006).

Another group of McBrearty and Brooks's (2000) traits has been found in Africa but not in Sunda, Sahul, or Tasmania (table 2). I suggest that these are traits that need not be considered essential to the recognition of modern human behavior in any part of the world. They should be considered less important in the definition of modern human behavior and in trying to understand the role of working memory in it despite the fact that they occur in Africa and in the Upper Paleolithic of Europe.

Alone among McBrearty and Brooks's (2000) traits, the long-distance exchange of materials involves all three of Noble and Davidson's (1991) cognitive criteria. Ambrose (1998, 2002, 2006, 2010, in this issue) has argued persuasively why issues of raw-material exchange and procurement should be interpreted as indicating modern human behavior in the Howiesons Poort industries of southern Africa and the late Middle Stone Age (MSA) of Kenya, but he also shows that the disappearance of that patterning may be a result of a situational response to changes of resource availability in a later, ameliorated climatic episode. Long-distance exchange occurred in Australia in historic times involving many materials, perishable and nonperishable, such as axes, adzes, boomerangs, pendants, human-hair string, grindstones, ceremonies, and the nicotine-based drug pituri (McCarthy 1939;

Mulvaney 1976), but the best indications are that it was probably only about 1,000 years old, with no indication that it went back more than 5,000 years. While modern human behavior may be necessary for some of these behaviors (but see my comments on blades; Davidson 2003), the absence of evidence of them should not be taken as indicating the absence of modern human behavior. One of the most characteristic features of modern human behavior is the new opportunities that opened up as a result of the enhanced cognitive abilities. Some of those features said to be characteristic of modern human behavior may actually be secondary to the more fundamental cognitive abilities that made such innovation possible. At the same time, such behaviors are an indication that another feature of modern human behavior is that people have acquired the capacity to engage in planned and conceptualized behaviors if they are appropriate or not to engage in those behaviors if they do not want to. The very option not to be stereotyped in behavior is an important part of modernity and undermines the notion that modernity is characterized by a whole "package" of traits (as argued by Habgood and Franklin [2008]).

Finally, there is a group of McBrearty and Brooks's (2000) traits that occurs in Africa and in Australia but not in Sunda (table 3). Given the paucity of evidence from the whole region between the Bab el Mandeb and the Bird's Head Peninsula of New Guinea, it would be simplest to argue that these traits are absent simply because there is not enough evidence to recognize them.

In particular, the determination of the extent of geographic or temporal variation and of regional artifact styles (insofar as that can be separated from geographic variation) depends on an analysis of sufficient numbers of closely related sites to establish patterns across space and time, and that is clearly

Table 2. Supposed traits of modern human behavior not found in Sunda or Australia

Trait <sup>a</sup>	Cognitive class <sup>b</sup>	Africa (MSA) <sup>c</sup>	Sunda <sup>d</sup>	Australia <sup>e</sup>	Tasmania <sup>f</sup>
Standardization	2	Yes	No	No	No
Identification by artifact style	3	Yes	No	No	No
Long-distance exchange	1–3	Yes	No	No	No

<sup>a</sup>McBrearty and Brooks (2000).

<sup>b</sup>The cognitive class assessment is based on the theoretical aspects of modern human behavior identified by Noble and Davidson (1991): 1, information flow; 2, planning depth; 3, conceptualization. Those traits with none of the cognitive traits are omitted.

<sup>c</sup>MSA = Middle Stone Age.

<sup>d</sup>Balme et al (2009).

<sup>e</sup>Stern (2009).

<sup>f</sup>Davidson (2007).

not yet possible for Sunda and only slightly more possible in Australia. It is a reasonable prediction that further research in Sunda will produce evidence of long-distance raw-material procurement, self-adornment, notched and incised objects, and burial with grave goods. Whether specialized hunting continues to be included in the list of traits characteristic only of modern human behavior will depend on the final assessment of the ongoing reconsideration of Middle Paleolithic faunal assemblage formation processes (e.g., Gaudzinski 2006): the discovery of well-crafted wooden spears at Schönningen in Germany, dated about 400 tya, has generally been taken to have demolished the idea that hominins did not kill large animals (Thieme 1997, 2005; see also Haidle 2010, in this issue). But there are two reasons why hunting has been seen to be so important in human evolution: first, it represented a change in the diet to allow high-quality protein sources and, second, in hunting-and-gathering societies of the recent past, hunting was important because of the social organization associated with it (see, e.g., Binford 2001). It is arguable that the really important indicator of modernity is social organization rather than the technical ability to kill animals. But such social organization is much more difficult to establish from archaeology even though it may require more of the characteristic traits of working memory. Wynn and Coolidge (2004) emphasized that Neanderthals may not have had “closely scheduled seasonal systems” or other features of hunting and gathering in the historic period.

## The Evidence of Rock Art

In Australia, the earliest evidence that might be interpreted as symbolism has been found in the sites with the earliest dates for human presence. These are pieces of hematite with ground facets from Malakunanja 2 and Nauwalabila 1 in Arnhem Land dated by optically stimulated luminescence (OSL) around 53 tya (Roberts, Jones, and Smith 1993), although O’Connell and Allen (O’Connell and Allen 2004) advise skepticism about the certainty of the association between the dates and the artifacts found in the sediments. In New South Wales, 2,500 km south of the Arnhem land sites, ritual burial prac-

tices in the form of cremation and fragmentation of one body and the use of sprinkled ochre on the extended burial of the other at Lake Mungo (Bowler and Thorne 1976) date to about 41 tya by OSL dating of the burial infill (Olley et al. 2006).

By about 30 tya, there is evidence of the movement of materials over long distances, including ochres that are sourced from distant quarries found in 37-tya levels at Puritjarra in Central Australia (Smith, Fankhauser, and Jercher 1998; Smith, Prescott, and Head 1997) and the movement of scaphopod shells over distances of 500 km from their source to Riwi in the Kimberley dated to about 35 tya (Balme and Morse 2006). At the same date, ochre fragments began to appear in the sediments at Riwi (Balme 2000).

Art was almost certainly part of the cultural repertoire of the first Australians in the form of personal ornaments, burials, and ochre processing—including its long-distance movement—and probably regionally distinctive early art styles of engraving and painting (see summary in Balme et al. 2009; P. Veth, N. Stern, J. McDonald, J. Balme, and I. Davidson, unpublished manuscript). The most secure dates are from sites where art is covered by dated sediment. Painted figures in the Kimberley have been dated to 17.5 tya by OSL on sand grains in a wasp nest said to be superimposed on a stylistically distinctive figure (Roberts 2000), and a rock slab excavated at Carpenter’s Gap dated to >39 tya has been shown to be covered with ochre (O’Connor and Fankhauser 2001). At Sandy Creek 1, in Cape York Peninsula, in addition to finding ochre pieces down to a date of 34.4 tya, Morwood excavated an engraved fragment fallen from the wall in levels dated to 14.4 tya (Price 1995). An engraved panel at Early Man site in Cape York Peninsula was covered by sediments dated to 16 tya (Rosenfeld, Horton, and Winter 1981:9–12, 30).

There are controversial arguments that some of the images represent species of megafauna that became extinct early in the first colonization (Akerman and Willing 2009; Chaloupka and Murray 1986; Lewis 1986; Murray and Chaloupka 1984; Ouzman et al. 2002), but the clearest examples are of the Tasmanian “tiger” extinct on the mainland after the arrival of the dingo about 4.5 tya (Mulvaney 2009). There are also

Table 3. Traits of modern human behavior found unevenly across Sunda and Sahul

Trait <sup>a</sup>	Cognitive class <sup>b</sup>	Africa (MSA) <sup>c</sup>	Sunda <sup>d</sup>	Australia <sup>e</sup>	Tasmania <sup>f</sup>
Geographic variation	3	Yes	No	Early axes only in north	No (?)
Temporal variation	3	Yes	No	Axes drop out and reappear later	Stop eating fish
Long-distance raw-material procurement	1, 2	Yes	No	100–125 km, >37 tya	Yes
Specialized hunting (danger)	2	Yes	Little evidence	Megafauna?	Yes
Regional artifact styles	2	Yes	No	Axes	No
Self adornment (beads, etc.)	3	Yes	No	Yes	Yes
Notched and incised objects	3	Yes	No	Yes	Yes
Burial with grave goods	3	Yes	No	Yes	Yes
Intensification	1	?	Cannot tell	Cannot tell	No

<sup>a</sup>McBrearty and Brooks (2000).

<sup>b</sup>The cognitive class assessment is based on the theoretical aspects of modern human behavior identified by Noble and Davidson (1991): 1, information flow; 2, planning depth; 3, conceptualization. Those traits with none of the cognitive traits are omitted.

<sup>c</sup>MSA = Middle Stone Age.

<sup>d</sup>Balme et al (2009).

<sup>e</sup>Stern (2009).

<sup>f</sup>Davidson (2007).

images known as “archaic faces” (Walsh 1988:68–73) that are heavily weathered, highly patinated, and often significantly geologically altered (Edwards 1968) in all conditions of dip, strike, exposure, and petrology. It has been suggested that these distinctive images are so generally weathered that they may be very old (McDonald 2005). Similar motifs are found at several sites across the arid zone between the Dampier Archipelago and Central Australia, with some more questionable examples as far away as western Queensland. Some of these are almost certainly relatively recent (David, Chant, and Flood 1992).

Dates for pigment found in oxalate crusts at sites in north-east Queensland reach 29 tya in Laura (Cole and Watchman 2005; Watchman 1993) and 32.6 tya in Chillagoe (Watchman 2001). Although there is no way to establish whether this dated pigment was part of a painted motif, these results suggest that we should not be surprised to date art elsewhere in Australia older than 30 tya. A conservative view would point to younger ages from other sites where direct dating has been applied (Watchman 2001).

Changing inventories of species also demonstrate major environmental change from the Pleistocene, when the sea was more than 200 km distant, to the early Holocene in the paintings of Kakadu (Chaloupka 1999) and the petroglyphs of the Dampier Archipelago, where images (including archaic faces) can be found on islands that were once hilltops but now are 5 km from the nearest land. This distance seems out of reach of the log-balancing craft recorded historically, and in the Dampier case, there is good evidence of differential weathering of the supposedly older images (Lorblanchet 1992).

It is traditional in Australian archaeology to be very skeptical of rock art dates and to avoid integrating the results into syntheses of early Australian behavior. But these well-documented sequences across the northwest (in Kakadu, the Kimberley, and the Dampier Archipelago) show divergent regional

art traditions in the Pleistocene that suggest that there was symbolic differentiation of populations early in the process of colonization. Early Australians were already making their distinctive marks by the symbolic structuring of their relationships with the environment and each other. To do no more than be skeptical about the rock art may be to undervalue the story it tells about the cognitive abilities of early Australians.

### Australian Evidence for Modern Cognition, Working Memory, and Integrated Cognitive Systems

After such a detailed discussion of the evidence in a framework different from that for this issue, the question is whether this tells us about the working-memory capacities of the first Australians and whether we have learned anything by concentrating on the Australian evidence. I approach these questions by taking a series of characteristics of the executive functions of working memory from the analysis of Coolidge and Wynn (2005) and doing a very preliminary assessment of their role in each of McBrearty and Brooks’s (2000) traits of modern human behavior identified in both MSA Africa and in Australia and that survived the detailed scrutiny here. These judgments are shown in table 4. As this is a preliminary consideration, there will be room for debate about the allocation of characteristics to traits.

A couple of features emerge very clearly. First, not all of the supposed traits of modern human behavior exhibit all of the characteristics that have been associated with enhanced working memory. Second, procedural memory seems to be a feature of only three of these behaviors, so it may not be exclusively associated with enhanced working memory. This is something of a relief for those who argue for a late emer-

Table 4. Preliminary matrix of associations between established traits of modern human behavior (as shown by the archaeological records in Africa and Australia) and aspects of working memory and executive function

Trait	Cognitive class	Organization of space and time	Planning	Forming associations between related events	Imitating and learning from others without dangers of trial and error	Goal attainment	Creative and socially productive	Memory of visual patterns	Memory of spatial locations	Evaluate success or failure	Sequential memory	Temporal-order memory	Selective inhibition	Flexibility	Procedural memory
Increased diet breadth	1	Yes			Yes					Yes					
Long-distance raw-material procurement	1, 2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes			
Specialized hunting (danger)	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
Regional artifact styles	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes				Yes		
Range extension to previously unoccupied regions	2		Yes	Yes	Yes	Yes	Yes			Yes	Yes			Yes	
Greater control of fire	2, 3	Yes	Yes	Yes		Yes				Yes	Yes				
Hafting and composite	2, 3	Yes	Yes	Yes	Yes	Yes		Yes		Yes	Yes	Yes			Yes
Notched and incised objects	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes			
New tool materials	3	Yes	Yes	Yes	Yes	Yes			Yes	Yes				Yes	
Temporal variation	3	Yes	Yes	Yes		Yes	Yes								
Geographic variation	3	Yes	Yes	Yes	Yes	Yes		Yes	Yes				Yes		
Special-purpose tools	3	Yes	Yes	Yes	Yes	Yes						Yes			Yes
Use of pigment	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes				Yes		
Self-adornment (beads, etc.)	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes				Yes	Yes	
Image and representation	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes		Yes
Burial with grave goods	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes				Yes		

gence of this sort of modernity, because good arguments can be mounted for the involvement of procedural memory in some stone tool industries from the Middle Paleolithic (see, e.g., Wynn and Coolidge 2004) and, in the view of some, earlier still. The case has been made that procedural memory can be found among monkeys and apes (e.g., Gibson and Jessee 1999).

By this judgment, we should probably also suggest that flexibility is a relatively unimportant characteristic, but the cases may be different. Wynn and Coolidge (2004) argued that procedural memory is an essential component of the knapping routines of the Levallois technique and indicates that Neanderthals had long-term working memory, but it may be that many of the other characteristics of human working memory are possible without procedural memory. The counterargument would be that flexibility is probably made possible by enhanced working memory but that there are many manifestations of it that do not automatically entail flexibility. This is consistent with the argument advanced earlier about stereotyped behavior. This is an important opposition that will need to be clarified in developing this matrix of associations.

At this stage, I do not want to say much more than this except to point out that this patterning would be consistent with a mosaic emergence of different aspects of working memory—something that Coolidge and Wynn (2005) hinted at—but this is problematic, too. What seems to be missing is a process of evolutionary change from a creature without the characteristics of working memory or executive function to one that has them. As Wynn and Coolidge (2010) say, “[executive functions] must have evolved during the course of human evolution” (S6). The questions that arise are the following: what was the process of emergence—was there any patterning to the emergence of different tiles of the mosaic—and what did a cognitive system look like before it ended up looking like Baddeley’s working memory? Klein (2000) and Wynn and Coolidge (2004) lean heavily toward an emergence derived from genetic change, but without more specific identification of the responsible genes and a strong argument about the interaction of genes and cognition, such appeals to genetic change sound rather like religious texts that summon miracles to account for events they cannot understand. I think there are good arguments that make that unlikely. So far, most prime genetic candidates have been shown to be problematic (Davidson 2010a), as is the case of *FOXP2* (Diller and Cann 2009), *MCHP1*, and *ASPM* (Rushton, Vernon, and Bons 2007).

The model developed by Barnard and colleagues (Barnard et al. 2007, 2010b) offers a way forward. In this, as I understand it (and oversimplify it), Barnard has taken his model of human cognition composed of nine interacting subsystems, worked with Byrne (e.g., Byrne 2003) to model ape cognition with six related subsystems, and produced a logical argument that there must be intermediate steps with seven and eight subsystems that have existed only among now-extinct hom-

inins. The final differentiation was from the eight-subsystem model to the nine-subsystem model that accounts for modern humans. The crucial difference arose with the emergence of a propositional system that takes its inputs only from the abstractions that have taken place in other systems. Only this subsystem can allow people to think about things for which there is no direct stimulus from the external environment. This transition, I suggest, is consistent with an argument for the emergence of reflexive meaning identified through the use of symbols and language (Davidson and Noble 1989).

We now have some more sophisticated models with which to test the nature of hominin cognition. This will allow us to consider a wide range of topics, such as the move from imitation to emulation, from knowing how to knowing that; the role of ritual in reinforcing memory (Ross and Davidson 2006) and the role of rock art in the marking and memorializing space; how a working-memory model might look in creatures that had not yet, for one reason or another, evolved a phonological loop or language; the role of material objects in selection of cognitive abilities (Davidson and McGrew 2005; see Hutchins 2005); and the creation of material objects specifically to prompt memory.

Finally, there is a question that keeps coming up when we think about the cognition of hominins and how human cognition emerged from it: to what extent is our perception about cognition biased by the fact that so many understandings of unimpaired cognition derive from inferences about people whose cognition is impaired in some way? Wynn and Coolidge (2010), for example, cite Coolidge, Thede, and Young (2000) as indicating the heritable genetic component of executive functions, yet this is a study dependent on assessment of people with behavioral disorders. In addition, Wynn and Coolidge (2004), while advising caution about the use of studies of people with frontal lobe damage, suggest that these might give some insight into Neanderthal personality. Is our understanding of the evolutionary emergence of modern human cognition inhibited by cognitive models that have been developed through attempts to understand the cognitive conditions of impaired modern humans rather than being based on an understanding of cognitive states of unimpaired ancestors?

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# Working Memory, Neuroanatomy, and Archaeology

by Rex Welshon

First, I categorize the papers presented in this issue according to a particular scheme: (a) those that support Wynn and Coolidge's hypothesis that enhancement of working memory probably played a significant role in cognitive evolution in the *Homo* lineage, (b) those that expand understanding of working memory, and (c) those that criticize Wynn and Coolidge's hypothesis. Second, I comment on the papers so categorized, focusing on the explanatory utility of working memory for particular cognitive advances in the *Homo* lineage as confirmed by archaeology and the computational prowess implied by those advances. Third, I suggest some avenues for future discussion, including what I think are two critical needs: first, clarification of what modern thinking is supposed to consist of and, second, clarification of what working memory is supposed to be. Finally, I make a methodological suggestion for embedding cognitive archaeological research in a larger research framework of comparative primate cognitive neuroscience.

First, I categorize the papers in this issue according to a particular scheme. Second, I comment on the papers so categorized. Third, I suggest some potential avenues for future discussion. Finally, I make a methodological suggestion for embedding cognitive archaeological research in a larger research framework of comparative primate cognitive neuroscience.

## Categorizing the Papers

Some of the papers in this issue support Wynn and Coolidge's (2010) hypothesis that a change in working-memory capacity sometime in the past 100,000 years propelled *Homo sapiens* past Neanderthals, some discuss working memory itself, and some criticize Wynn and Coolidge's (2010) hypothesis. The first group of papers—those by Wynn and Coolidge (2010), Rossano (2010), Wadley (2010), Haidle (2010), Nowell (2010), Davidson (2010), and Bruner (2010)—is the largest. To varying degrees, these seven papers assume the validity of working memory and apply it to cognitive development in the genus *Homo*, providing archaeological, paleoethnographic, and paleoneurological evidence supporting the evolutionary enhancement of working memory and the role such enhancement plays in the emergence of uniquely modern cognitive abilities. Six papers focus more on the model of working memory itself than on its application to phylogenetic

cognitive development. These papers expand our understanding of working memory and identify problems with it; some also apply that expanded understanding to certain cognitive developments. In this group are the papers by Engle (2010); Aboitiz, Aboitiz, and García (2010); Barnard (2010); and Reuland (2010) and parts of those by Ambrose (2010) and Beaman (2010). Finally, four of the papers—those by Belfer-Cohen and Hovers (2010) and Martín-Loeches (2010) and parts of those by Beaman (2010) and Ambrose (2010)—offer cautions against identifying a cognitive revolution based on enhanced working memory.

Of course, no paper fits entirely into one category, and all papers have implications for the others. This is a hallmark of a healthy research program—a proposed theoretical model, supported by empirical data, is extended by applying it to new data domains. Those new data sometimes prompt small refinements to the theoretical model, at other times a larger adjustment, sometimes significant rethinking, and sometimes rejection of the model. Each alternative is represented by at least one paper.

## Setting the Scene: The Function and Neuroanatomy of Working Memory

Working memory is, according to Baddeley's latest formulations, composed of four components: first, a visuospatial sketch pad; second, a phonological loop; third, a central executive; and, fourth, an episodic buffer. As Engle (2010) notes, working memory is broader than vision and audition. Recent work suggests that there may also be a gustatory palette, an

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**Rex Welshon** is Associate Professor in the Department of Philosophy, University of Colorado (Colorado Springs, Colorado 80993, U.S.A. [rwelshon@uccs.edu]).

olfactory store, and a tactile-textural touch pad. But the emphasis on vision and audition reflects their importance in understanding modern human behavior.

The *phonological loop* is composed of two subsystems, the *phonological store* and the *articulatory loop*, the first of which is a temporary storehouse of sounds and the second of which is responsible for sound production. The *visuospatial sketch pad* is likewise composed of two systems, the first devoted to processing qualitative pattern information such as color, texture, and shape, and the second devoted to processing spatial location and sequential movement information. The *multimodal central executive* is responsible for attention, behavior inhibition, decision making, sequencing, and integrating the information from the phonological loop and the visuospatial sketch pad. The *episodic buffer* integrates and temporarily stores information from different sources, including long-term memory, as a single, bound episode. The episodic buffer is under central executive control, which retrieves stored information in conscious awareness, reflects on it, and modifies it if needed.

Engle (2010) discusses certain methodological issues that working-memory measurement provokes, and the longest section of the paper is a discussion of the reliability and validity of working-memory capacity. I do not pause to comment on this discussion. I propose instead to emphasize Engle's (2010) distinction between trait and state variable. Working memory is typically conceived as a relatively fixed characteristic, but it is also a state variable whose proper functioning depends on environmental context (see Schmeidel 2007). In particular, working-memory capacity varies as attention capacity varies. It is, thus, also an attentional ability with differential capacity for blocking distracting events. It is not currently known whether this differential capacity is a result of keeping more information in working memory or of moving information from inactive to working memory.

As so far discussed, working memory is a functional cognitive model of a certain class of psychological phenomena. Physically minded scientists expect this cognitive model to be realized neurally. The past 15 years have seen quite remarkable advances in establishing neural correlates for a wide array of psychological phenomena, and the phenomena that comprise working memory are no exception. Because much of the excitement about working memory in discerning its role in cognitive evolution has so far focused on the phonological loop, consider its neural realization in greater detail.

The neuroanatomical basis of the phonological loop is, as Aboitiz, Aboitiz, and García (2010) report, generally agreed to be a circuit of pathways in particular regions of the brain connected by tracts of myelinated neurons. The phonological store of auditory information correlates with activity in the inferior parietal lobe at the supramarginal gyrus (Brodmann area 40) and posterior superior temporal lobe (Brodmann areas 39 and 41)—together, Wernicke's area. In auditory perception, two pathways—one dorsal, one ventral—proceed from this temporo-parietal region. The dorsal pathway con-

nects via the myelinated neurons of the arcuate fasciculus to the dorsolateral and ventrolateral prefrontal cortex (VLPFC), while the ventral pathway connects via the uncinete fasciculus to the VLPFC. Although both dorsal and ventral pathways connect to the VLPFC at Brodmann areas 44 and 45 (Broca's area), some evidence suggests that distinct subregions within Broca's area separately process dorsal and ventral information. It is also generally agreed that the VLPFC is the neural locale of the phonological loop's articulatory rehearsal loop.

In perceptual neuroscience, the ventral auditory pathway is often referred to as the "what" pathway and the dorsal pathway as the "where" pathway. But this characterization, made on an analogy with the visual ventral "what" and dorsal "where" pathways championed by Goldman-Rakic and many others, fails to capture the complexities of the information carried by each. As Aboitiz, Aboitiz, and García (2010) point out, in order for the dorsal pathway in humans to do what Wynn and Coolidge (2010) need it to do, it must not simply locate the source of sound; it must also map acoustic *speech* signals to dorsolateral and ventrolateral prefrontal areas. But speech is not just sound—it is syntactically structured and semantically meaningful sound. This is a significant functional difference from auditory pathways as found in noisy but speechless monkeys, in whom there are well-developed ventral pathways but only incipiently developed dorsal pathways. This functional difference may be correlated with the absence in monkeys of the supramarginal gyrus (Brodmann area 40) and angular gyrus (Brodmann area 39). Does it therefore follow that supramarginal and angular gyri are "spoken-language areas"? Some have thought so, but the correct answer is probably no.

Using fine-grained measurement techniques and mathematical modeling, Bruner (2010) details paleoneurological findings that demonstrate nonallometric brain growth in inferior parietal regions through *Homo erectus*, *Homo neanderthalensis*, and *Homo sapiens*. Among the parietal regions experiencing disproportionate expansion is the supramarginal gyrus, which, as suggested above, correlates with phonological storage and the first stage of the auditory-perception dorsal pathway. As interesting as this finding is, it is at least as significant that *superior* parietal regions have also expanded nonallometrically over the same time period in *H. sapiens*. These regions, surrounding the intraparietal sulcus (IPS), have long been identified as visual and sensorimotor association areas. Mesulam suggested almost 30 years ago that it is in this region that our egocentric visuospatial map of the world is first cobbled together, thus implicating superior parietal regions in the emergence of subjectivity. Moreover, if subjectivity is implicated in agency—our status as a source of causal chains—then superior parietal regions are implicated in agency as well. And there is reason to think that this is true, for superior parietal regions also correlate with attentional and intentional activity. More recently, it has been found that IPS implements both nonabstract and abstract numerosity and that while prefrontal cortex implements basic numerosity

in children, IPS implements more symbolically mediated numerosity in older children and adults (Franklin and Jonides 2009).

Neurological evidence for nonallometric frontopolar (Brodmann areas 9, 10, and 46) expansion is discussed by Nowell (2010) and Ambrose (2010). This area is, in humans, disproportionately larger than the homologous area in chimps, and it appears that much of its expansion occurred with the emergence of *H. erectus* 1.8 mya. Frontopolar function is not as well understood as the function of other regions of the brain, but it is generally agreed to include planning, organization, and inhibition. Nowell (2010) also reports on parallel and corroborative research suggesting that early weaning, postmenopausal survival, and expanded childhood in Middle Pleistocene populations of *H. erectus* and *H. neanderthalensis*, all significant changes from *Australopithecines* and pongids, also correlate with expansion of particular cranial regions.

## Expanded Working Memory's Significance in Cognitive Evolution

Taking these neuroanatomical and neurofunctional data on board, is there evidence that supports the claim that cognition has developed during the career of the genus *Homo*? The answer is, of course, yes, with some of it being provided in the papers by Haidle (2010), Nowell (2010), Rossano (2010), Davidson (2010), and Wadley (2010). Haidle (2010), Nowell (2010), and Rossano (2010) discuss some early developments in the line; Davidson (2010), Wadley (2010), and Wynn and Coolidge (2010) discuss later developments.

As Haidle (2010) points out, lots of animals, from crows to sea otters to bottlenose dolphins, use tools. But even when members of these species use more than one tool, they are neither constructed nor modified and are, moreover, used for a single purpose. With chimps, on the other hand, significant differences emerge: chimps *make* tools, they use a lot of *different* tools, they use tools for *multistep* processes, and they use tools for a lot of different *reasons*. That is, chimps are significantly more flexible both in tool type and in the uses to which tools are put than are other mammals (other than humans), and that flexibility is a distinctly cognitive flexibility. Their use of tools in multistep termite extraction in particular suggests integration of long-term memory stores with working memory.

Oldowan lithic technology is additionally complex. *Homo erectus* knapped tools more than 1 million years ago, and that they did so presupposes subacute needs and a modicum of planning, which in turn implies that cognitive time depth extends into both the future and the past. An interesting—and currently unanswered—question is how far into the future and how far back into the past particular tasks require cognitive time depth to extend. Although extending time depth does not imply verbal communication, much less speech, and therefore does not imply that extensive phono-

logical stores or rehearsal capacities were developing even then, it is consistent with thinking that the visuospatial sketch pad had already developed beyond abilities found in other primates. But the relative stability of lithic technology during the Acheulian period, discussed by Nowell (2010), suggests that *H. erectus* and *Homo heidelbergensis* lacked some additional neurocognitive development—or failed to take advantage of a neurocognitive development already in place—that found expression in the lithic technologies of *Homo neanderthalensis*.

The appearance of wooden spears 350 kya and, shortly thereafter, the appearance of hafted weapons suggest further cognitive advances. As Wadley (2010) shows in an analysis of fiber and adhesive hafting, hafting is an extended construction period that requires ongoing planning and constantly refreshed episodes of phasic attention and intention formation. Such modular and composite construction techniques also decouple satisfaction and basic need, for manufacturing tools becomes a goal that yields its own satisfaction. Modular construction and organization techniques develop gradually over the next 200,000 years, with *H. neanderthalensis* first leading the way and then *Homo sapiens sapiens* taking over. Suffice it to say, as Belfer-Cohen and Hovers (2010) argue, even in the Middle Paleolithic, our precursors had phasic attentional and planning capacities significantly enhanced compared with those of earlier species of the genus and not obviously as impoverished as Wynn and Coolidge (2010) have it. So, perhaps working memory underwent enhancement a good deal earlier or more gradually than suggested. Alternatively, perhaps enhanced working memory does not explain the difference between *Homo sapiens* and Neanderthals at all.

Rossano (2010) comes to the issue of cognitive development from a different angle, that of symbolic activity and its precursors. He uses Peirce's analysis of signs as his jumping-off point. A sign is a referring device, and it accomplishes its referential duty by being either an icon, an index, or a symbol of its referent object. Icons are perceptually similar and stimulus-dependent referring devices: red ochre is, for example, an iconic referring device, perhaps to blood. An index, while stimulus dependent, need not be perceptually similar to the referent object in order to refer to it: beads, for example, may indexically refer to group membership or social status, and a wrinkled nose conjoined with a scowl may index disgust. Finally, a symbol is neither perceptually similar to its referent object nor stimulus dependent. Rather, a symbol is a stimulus-independent referring device whose referent object is fixed by social convention. The word *bank* looks neither like the edge of a river nor a building used to keep money safe, and its referential job is accomplished even in the absence of any occurrent stimulus. Our agreement that *bank* refers as it does is sufficient for it doing so.

Rossano's (2010) use of Peirce's analysis of signs expands on it in a way characteristic of work found in many social sciences. On this more general understanding, not only do signs refer to concrete particulars, they also represent and

signify abstract and social properties such as health, group membership, social status, and aesthetic talent. On the basis of this more general understanding, Rossano (2010) identifies the first appearance of iconic signs at 3 mya, the first appearance of indexical signs at 135 kya, and the first appearance of symbols at 77 kya. This places emergence of symbolic activity in the period after Neanderthals chased *H. sapiens* from the Levant 80 kya and before the *H. sapiens* flood poured out of Africa again around 50 kya.

Martín-Loeches (2010) argues similarly that Wynn and Coolidge (2010) miss the time frame by several tens of thousands of years. He notes, among other things, that even if enhanced working memory plays a role in the cognitive difference between Neanderthals and modern humans, it is not a sufficient explanation of that difference, for the repertoire characteristic of modern humans also includes other complex cognitive activities such as art. According to Martín-Loeches (2010), Wynn and Coolidge (2010) date the emergence of the modern human mind to 30–40 kya, the same time frame during which therianthropes appear. But Martín-Loeches (2010) argues that the time should be pushed back at least another 40,000 years to the Blombos Cave engravings. Granted, far fewer examples of decoration exist before 40 kya than subsequent to it, but this may be a difference only in quantity, not in quality. Of course, that evidence of decoration before 40 kya is absent is also consistent with there being an absence of decoration before 40 kya.

## Expanding Understanding of Working Memory and Affiliated Systems

A number of the papers develop working memory and other cognitive models, thereby laying the groundwork for subsequent applications to the archaeological record. Aboitiz, Aboitiz, and García (2010) provide an account of working memory's role in language development that is quite sympathetic to Wynn and Coolidge's (2010) approach. Aboitiz, Aboitiz, and García (2010) concur that recursion is necessary to our fully developed form of language and suggest that enhanced phonological storage plays a crucial role in its emergence. As already noted, the dorsal pathway from Wernicke's area to the prefrontal cortex is, at a minimum, significantly augmented within the *Homo* line. Of course, that does not explain language emergence unless it underwrites particular linguistic abilities. But, according to Aboitiz, Aboitiz, and García (2010), it does—the dorsal pathway between BA 44 and the posterior temporal cortex and supramarginal gyrus is correlated with syntactical abilities to parse sentential units and hierarchical grammatical structures. Hence, working memory is implicated in syntactical comprehension. Furthermore, working memory is what underwrites our ability to store transiently and keep track of long-distance syntactical dependencies, such as embedded clauses and sentences, characteristic of recursion.

Barnard's (2010) paper presents an ambitious model that

embeds working-memory development in a larger theoretical environment of cognitive architectural changes that underwrite increasingly complex, mediated, and abstract responses to the environment. On this model, working memory is, in general, an emergent property of a system of interactions between specialist subsystems.

All mammals are capable of learning. As one climbs the phylogenetic ladder, one finds more advanced forms of cognition. Taking the mammalian mind as found, say, in cats and zebras, one discovers dedicated acoustic, visual, gustatory, olfactory, and tactile sensory-processing systems; interoceptive systems for processing pain, thirst, air hunger, and various affective states; proprioceptive systems for processing balance and relative position of bodily parts; and associative perceptual systems responsible for binding the output of these specialized subsystems into synthesized and unified experience. Some of the characteristic features of such mammalian minds are that they have a number of parallel routes for guiding action, they have few mediating cognitive levels that interrupt the circuit from input to motor behavior output, and they utilize heteromodal binding as the final processing step before motor behavior initiation.

Monkeys and primates add new architectural subsystems to those found in other mammal brains. The first is an *effector* subsystem that mediates muscle control, as opposed to the more direct route from heteromodally bound perceptual experience to muscle contraction. This effector system is properly a transmodal associative system, taking the input of heteromodal associative subsystems and outputting more cognitively nuanced muscle coordination. The other new subsystem is a *spatial-praxic* subsystem, which carves out abstract relationships necessary for visuospatial control of action.

Subsequent to these new abilities, found first in monkeys, there are, Barnard (2010) hypothesizes, three further transitions found in hominins, chimps, *Australopithecines*, and species in the *Homo* genus. The first is a new *auditory-verbal* subsystem that parallels visuospatial-praxis abstraction. Just as a spatial-praxic organism—monkeys and orangutans are examples—has newly evolved cognitive abilities to control its more dexterous hands and limbs, so, too, does an auditory-verbal organism—such as a Neanderthal—have newly developed executive and motor abilities for controlling breath suppression, lip and tongue control, and volume modulation in their newly evolved mouth structure. These executive and motor abilities underwrite the production of phonological patterns used as indexical referring devices to distal objects and events.

Once phonological patterns are established in the auditory subsystem and become independent of other multimodal contingencies, a second novel subsystem emerges—the *morpho-lexical* subsystem. An organism with morpho-lexical cognitive architecture can compress encoding into vocal invariants, thus liberating representation from iconic similarity and indexical stimulus dependence and prompting a quantum leap in representational efficiency. For the first time,

sounds encode information into word chunks that have the capacity for productive verbal and spatial-praxic imagery and representation, ushering in the ability to imagine, plan for contingencies, and react physically and emotionally to counterfactual states of affairs. Of course, the ability to imagine counterfactuals and to rehearse responses to them places additional demands on executive function for directing attention to salient input from the multimodal spatial-praxic, auditory, and morphonolexical loops.

At this juncture, Barnard's (2010) model intersects Baddeley's model of working memory, for the multimodal spatial-praxic and morphonolexical representational loops map to working memory's visual sketch pad and phonological loop, respectively. However, while mapping to working memory, Barnard's (2010) model has another transformation to explain. Morphonolexical organisms are capable of high levels of abstraction, and with these abstractive capacities, the need for organizing intersections between vocal and spatial-praxic information becomes acute. This, according to Barnard (2010), is the crucible in which semantic reference and meaning are forged. As reference becomes independent of the other multimodal subsystems, a new and final subsystem emerges dedicated to processing propositional meaning. This *propositional* subsystem requires the capacity to abstract away from the emotional content of what a proposition represents and gives a propositional organism the capacity to engage in metacognition and monitoring. So, in addition to being able to talk about making a tool, a propositional organism can plan to make a better tool, think about what others might think about their tools, and think about out-of-sight others.

Where Barnard (2010) provides a theoretical model of the changes to working memory necessary to support semantic reference, Reuland (2010) shows what is necessary for working memory to support a full-fledged and recursively structured language. The key cognitive capacity that jump-starts recursivity is planning. Planning, as many of the contributors emphasize, depends on imagination, which requires counterfactual representation of some aspect of the world distinct from the way the world actually is, and goal and sequence setting, which require means-end reasoning abilities. Focus on the former. Planning requires two representations: an accurate representation of some state of affairs as it actually is and a counterfactual representation of a state of affairs as it is intended to become. To plan, the mind must be sufficiently robust to hold both representations in mind. While the visuospatial sketch pad is clearly implicated in this task, it is limited to iconic representation. Language, being symbolic, is neither tied to its referent by perceptual similarity nor bound to its referent by occurrent stimulus. Language's symbolic referential capacity unlocks a riot of combinatorial representational possibilities. Unique among systems of communication, language permits combining semantic meanings willy-nilly just to see what happens.

Nonhuman hominins such as chimps and bonobos have systems of expressive communication; they have elements rep-

resenting form/meaning combinations, a conceptual system, an interpretation system, memory systems, and planning capacities. But at least in the wild, they do not have language at all, and despite their ability to use and even combine a few symbols when intensively trained in captivity, their linguistic abilities top out at the level of a 3-year-old human. What is the difference? Fitch, Hauser, and Chomsky (2005) and Hauser, Chomsky, and Fitch (2002) have proposed that symbolically competent nonhuman hominins lack recursion abilities. Even if, as some claim, this is not the only difference between human and chimp linguistic abilities, it is a unique difference, for while one can imagine gradual changes in articulation, breathing suppression, vocal range, and lexical access, one is hard-pressed to imagine gradual changes in recursivity, which is all or nothing.

I will fly over Reuland's (2010) lengthy discussion of recursion, binding, and other fascinating grammatical phenomena and pick up the discussion again at the section "Locality," in which Reuland (2010) proposes that it is not working memory per se that is involved in the cognitive revolution that separates *Homo sapiens* from the Neanderthals but a particular component of it—the declarative-procedural interface. The declarative-procedural interface is, at least in the work of Michael Ullman (2004), an interface between two neurally modeled memory subsystems. Procedural memory is an encapsulated and largely unconscious system of long-term and working memory that underwrites motor and cognitive skills involving sequences. As a set of rules that govern proper concatenation, grammatical memory is procedural. Declarative memory, on the other hand, is a nonencapsulated and largely conscious system of long-term and working memory. As a set of consciously entertained meanings, lexical-semantic memory is declarative.

Adding recursion—a grammatical, procedural linguistic feature—to existing referential words—a semantic, declarative linguistic feature—is the evolutionary bottleneck in language development, for functional limitations on that declarative-procedural interface entail restrictions on recursion, which in turn entail constraints on the combinatorial capacity of language. Martin-Loeches (2010) describes and diagrams some of the differences between a neural network that can and one that cannot subserve the comprehension of recursively structured sentences. But this functional bottleneck between two memory systems suggests that a parallel neural bottleneck also had to be relieved. Easing the block could have been achieved by the appearance of new brain regions or pathways, by expanding existing regions or pathways, by a change in connectivity between existing neural regions, or by a change in signal transmission efficiency. Reuland nominates a change in Broca's area, but there is no reason to think that the others are not also involved. For example, the human anterior intraparietal cortex and the supramarginal gyrus are heavily connected by the myelinated neurons of the arcuate fasciculus to Broca's area. Changes to either or to the arcuate fasciculus



bundle, if confirmed to have occurred within the *Homo* line, could also be implicated.

## Skepticism about Working Memory

There are, no doubt, plenty of reasons to be skeptical about the hypothesis that enhanced working memory explains cognitive development, but I focus on three. First, one might argue that working memory is variously characterized and that because it is equivocally understood, it is not univocally applicable. Second, one might argue that while working memory is well individuated, it is not alone *sufficient* to explain that which it is invoked to explain. Third, one might argue instead that well-individuated working memory is not even *necessary* to explain that which it is invoked to explain. Each alternative is represented by at least one paper.

The most direct attack on the hypothesis is to reject the explanatory linkage between working memory and cognitive development, and a quick strategy for accomplishing that is to suggest that working memory is a mongrel category. Beaman (2010) and Martín-Loeches (2010) both argue that this is the case. The different theoretical levels at which working memory is characterized can, for example, lead to conflating results relevant for one with those relevant to another, as suggested by Martín-Loeches (2010). Neurologically, working memory refers to sustained neural firing. However, sustained neural firing is a general computation strategy exemplified throughout the nervous system and found in many of its subsystems, so there is nothing unique to *Homo sapiens* about it. Functionally, the phonological loop is a set of persistent activation patterns of information recalled from long-term memory. Here, enhanced working memory is enlarging the number of simultaneously activated neurons. Hence, a genetic explanation for an increase in neural number and/or neural circuit complexity or additional metabolic resources for keeping large numbers of neurons activated is the most likely way forward for evolutionary cognitive neuroscience.

Wynn and Coolidge (2010) consider but reject the idea that a single additive mutation could be responsible for late working-memory enhancement. Martín-Loeches (2010) adds an additional reason to be skeptical. One candidate for that single additive mutation—*FOXP2*—is no longer credible because, as things turn out, Neanderthals had *FOXP2*. It is more likely that multiple gradual phenotypic changes correlate with multiple genotypic changes leading to modern human cognitive capacities. But we will not know which genetic changes are relevant, much less implicated, until more comparative research is available.

Beaman (2010) notes that there are at least three different concepts of working memory: Baddeley's model of a short-term codification system for perceptual information, Miller's model of a system that facilitates rapid access to goal-relevant information, and Cowan's model of an attentional focus system. Such ambiguity is not in itself damaging to explanations invoking working memory, but it does entail that those using

the category be explicit about which concept is operative. One way to reveal the commitment is to assess the needs for which working memory is supposed to be a solution. Wynn and Coolidge (2010) offer three needs: first, contingency planning, language, innovation, and analogy entail significant working-memory capacity; second, if cognitive development is an evolutionary adaptation, it must be a heritable genotype; and, third, cognitive fluidity (multi- and transmodal information integration) implies working memory.

I will not discuss Beaman's (2010) comments on heritability, but I am interested in his strategy with language processing and cognitive fluidity. He argues, contrary to Wynn and Coolidge (2010), that the phonological loop is not necessary for some of the processes they invoke it to explain. First, he argues that enhanced phonological storage is not necessary for language processing. Neuropsychological lesion studies show that defective phonological storage in adults results only in a small speech comprehension deficit and no speech production deficit at all. Other evidence is presented to corroborate the claim. Humans comprehend semantic meaning in as little as 150 ms, so claiming that *phonological* storage capacity is a prerequisite for *speech* comprehension or cognitive advancement is of doubtful utility. Likewise, increased phonological storage capacity is not necessary for recursion. While required for vocabulary acquisition, phonological storage is a component of declarative memory, whereas recursion is, as already suggested, a component of procedural memory.

For some of these criticisms there may be answers. Wynn and Coolidge (2010) cite studies that have found a difference between adults and children on phonological storage capacity. Even if lesion studies establish that degraded phonological storage capacity is not necessary for adult language processing, the studies cited by Wynn and Coolidge (2010) show that in children, phonological storage capacity is implicated in vocabulary development and size, utterance complexity and length, and syntactic complexity. Such differences between adults and children may have implications for the phylogenetic emergence of language. If so, the importance of phonological storage capacity is not yet resolved either way.

Attention is a more likely candidate for being a necessary condition for improved cognitive performance than enhanced phonological working memory. But this invokes the view of working memory as a controlled attentional system, not a system of short-term perceptual information storage. Of course, there are new problems with this suggestion—if working memory is a mongrel, attention is even more of one, referring to at least a dozen distinct phenomena. Beaman (2010) narrows discussion to focal attention and executive attention, only the latter of which—the ability to maintain or recover access to memory items in the absence of focal attention—is a viable necessary condition for improved cognitive abilities and, hence, a contender for cognitive evolution.

However, even when conjoined with enhanced phonological and visuospatial storage capacity, enhanced executive at-

tion is not sufficient for modern cognition and behavior, for one of the characteristic features of the evolving human mind is the ever-increasing incidence of complex goal-directed cognition and behavior, with its attendant planning cognition and behavior. And these capacities, if a result of enhanced working memory, utilize the model of working memory as a system that facilitates rapid access to goal-relevant information. Beaman (2010) discusses the adaptive control of thought-rational model of goal-setting and planning cognition, the details of which need not delay us. But he draws an interesting implication from its investigation, namely, that emotionally laden motivation must factor into goal-formation processes and that self-rewarding activities uncouple urgent need from satisfaction. We do not know yet whether specific neural changes underwrote specific cognitive changes or whether some minimal level of neural and cognitive change was sufficient for triggering the entire cascade of cognitive and affective changes that eventuated in the differences between us and Neanderthals.

## Future Discussion and a Methodological Suggestion

The conference was organized around the topic of working memory and the evolution of modern thinking. Reviewing the papers, it appears to me that there are disagreements about what modern thinking is, about what working memory is, and about what, if anything, an evolutionary explanation of modern thinking by working memory might come to in the end. In short, there is disagreement about the *explanandum*, about the *explanans*, and about the explanation of the former by the latter. That is three for three—a disagreement trifecta. The benefit of so much disagreement is that discussion is guaranteed. One drawback is that with so much disagreement, discussion may not be productive. I am sure everyone would be grateful were I to try to defuse some of the disagreements, but I will not. Instead, I offer some reflections that will only fuel more disagreement.

First, the *explanandum*—modern thinking—sorely wants specification. A recurring pattern of criticizing Wynn and Coolidge's (2010) hypothesis is to argue as follows. Wynn and Coolidge (2010) identify some cognitive quality *F* as a feature of modern thinking that distinguishes *Homo sapiens* from *Homo neanderthalensis*. They affirm that *F* first appears *Y* thousand years ago, but there is evidence for *F* at *Y + Z* thousand years ago. Hence, *F* thinking extends back to that period, and, pace Wynn and Coolidge (2010), *F* is not what makes *H. sapiens* modern after all. Substitute for *F* representation, sign and symbol usage, modular construction, pigment use, planning, goal setting, art, language, and self-awareness, and one gets distinct instances of the argument form.

The argument form looks valid, so the work that needs to be done is to determine whether, for a given substitution of *F*, the resulting argument is sound. But notice the nature of this kind of work. For all submissions of *F* representation,

sign and symbol usage, modular construction, pigment use, planning, goal setting, art, language, and self-awareness (and whatever else one wants to throw in the hopper) and for all of the subsets in the superset of these features, it must be determined, as Davidson (2010) persuasively argues, which is merely an adventitious concomitant of modern thinking; which is a diagnostic symptom of modern thinking; which is a necessary, which a sufficient, condition for modern thinking; which is a necessary and sufficient condition for modern thinking; and which, if any, is an essential constituent of modern thinking. That is a big job. McBrearty and Brooks have done some of it, and Davidson (2010) does some more, but more still needs to be done.

One can try to finesse this job away by arguing that *modern thinking* is stipulatively defined. If so, then *modern thinking* can be defined any way one likes. But for an empirical science, such semantic legislation is unappealing. Alternatively, one can abandon the term “modern thinking” altogether and focus instead on the fractionated cognitive capacities previously brought under its umbrella. This has some promise, encouraging increased precision and fine grain. Yet fractionating modern thinking into its constituent capacities may hide emergent characteristics that, on reflection, better capture major shifts in cognitive style. Better, I think, to continue working in the muddy trenches but to acknowledge that vigilance is required to avoid the kind of circularity that Davidson (2010) identifies in his paper.

Second, the *explanans*—working memory—needs to be reined in. Another way to engage the Wynn-Coolidge (2010) hypothesis is to argue that their understanding of working memory is (a) wrong, (b) incomplete, or (c) ambiguous; that if any of *a*, *b*, or *c* is true, then their application of working memory to archaeological evidence is vitiated; and, hence, that they have failed to make the case they need to make in order to explain the evolution of modern thinking by working memory.

Even those critical of Wynn and Coolidge (2010) would agree that after the more than 15,000 articles in the past 20 years containing the term “working memory” in the title (Jonides et al. 2007), it is difficult for one's understanding of working memory to be just plain wrong. After all, it is quite likely that at least one article in this huge literature has fed one's pet psychological feature through the working-memory filter. Take the ever-busy phonological loop. Wynn and Coolidge (2010) employ this component of working memory to provide an explanation of the emergence of semantically rich, recursively structured language. While it is appropriate to ask whether the phonological loop can bear the burden, it is going a bit far to announce that it has nothing to do with the emergence of syntax or recursion. To see the point, ask yourself, what features of language cannot occur without expanded phonological storage? The concatenation of phonetic units into words? The well-formed syntax of sentences? The referential capacities of its singular terms? The meaningfulness

of its predicate expressions and sentences? The pragmatic forcefulness of its speech acts?

These are pertinent questions because it is all too easy to argue fallaciously that because speech is auditory input and the phonological loop processes auditory input, therefore the phonological loop processes speech. The undistributed middle is glaring, for even if the phonetic elements of speech are processed by the phonological loop's neural activity, its syntactical, semantic, and pragmatic features may not be. But it all depends on how much one is willing to load into the phonological loop. Wynn and Coolidge (2010) appear to be willing to load in quite a bit; others are more wary. But I do not see that Wynn and Coolidge's (2010) decisions are for that reason obviously *wrong*.

Understand that I am not carrying a brief for either side— as a philosopher, I am not paid to make the hard decisions. Rather, the suggestion is that working memory, even if only a cognitive model, is a contested category to be used with caution. If Ullman (2004) is correct that syntactical abilities rely on procedural rather than declarative memory and if the phonological loop's storage capacity is restricted to declarative information, then syntax is not part of the phonological loop. But note the ifs: Ullman's (2004) model of syntactical understanding is one among several and unusual among them for reducing syntactical memory to procedural memory. Second, even if syntactical understanding is a wholly procedural capacity, it may be that it can be incorporated into an enriched phonological loop—call it the phonosyntactical loop. It might even be seen as a precursor to, or as developing with, Barnard's (2010) morphonolexical system.

One kind of research that may help resolve uncertainties is contemporary neural correlate research that dissociates phonological, syntactical, and semantic features of language. Phonological dissociation studies have established that acoustic analysis and phoneme identification and representation are associated with a heteromodal network of activity that includes the bilateral posterior and middle superior temporal cortex, the left supramarginal gyrus of the parietal cortex, posterior superior regions of the left VLPFC, and the left supplementary motor area cortex (Friederici and Kotz 2003; Gold and Buckner 2002; Hickok and Poeppel 2007). A similar heteromodal pathway is discernible for visually experienced language (for review, see Démonet, Thierry, and Cardebat 2005).

Syntactical dissociation studies use a variety of techniques to tease apart syntactical and semantic understanding. Among these techniques are using jabberwocky sentences, sentences that are grammatically correct but composed of pseudo-words—“the delarish benatur snoffered nistardly”—or that instantiate category mistakes—“Toffer's ventral speech flies a snide anchovy to the four” (Friederici and Kotz 2003). Using these techniques, it has been found that syntactical word form identification is associated with heteromodal activity in the bilateral posterior superior temporal cortex, while word category identification is correlated with heteromodal activity in

the anterior superior temporal cortex and inferior portions of the left VLPFC (Dapretto and Bookheimer 1999; Grodzinsky and Friederici 2006; Sahin, Pinker, and Halgren 2006; for doubts, see Kaan and Swaab 2002; Spitsyna et al. 2006).

Suppose the dissociated neural correlates of phonological, morphological, syntactical, and semantic comprehension are found. In fact, suppose that the neural correlates of all of the cognitive abilities unique to modern thought are found. We are not even close to that day, but suppose it done. One might ask, as I imagine some at this conference might ask, what good is any of it? Correlations are cheap. Take as an example semantic meaning. It is unquestionable that there are neural correlates to the meanings of words and sentences. If you stick a person into the scanner and ask him or her to think of the meaning of “toast,” regions in the hippocampal, temporal, and parietal cortex will reliably fire. But does that imply that semantic meaning is in the head? Probably not. For, some connectionists notwithstanding, semantic meaning is *conventionally* fixed—if *and only if* we agree to it, anything can mean something else: a piece of cloth or an animal or a bird can mean a country; tugging at my ear can mean it is time to start the assassination attempt; the word “assassin” means a professional murderer; “Bournemouth” means the city at the mouth of the Bourne River. That is what is new about symbols as opposed to signs and icons. So, even were we to map out the neural correlates for every word's and every sentence's meaning, we will not have finished the job.

I am suggesting neither that representation and meaning are not physical nor that cognitive archaeologists are just shooting in the dark even if their hypotheses are neurally grounded. I do not know whether representation and meaning are physical or not, and cognitive science, whether of us or of our extinct ancestors, benefits from as much neuroscience as it can get. However, let us acknowledge that representation and meaning are quite peculiar cognitively and have yet to show any sign that they will easily yield to physical reduction.

Let us also remember the obvious: the epistemological distance between us and our ancestors is not just temporal and not just cognitive—it is physical as well. There are no Middle Paleolithic brains to compare ours with. One of the remarkable achievements of cognitive archaeology is that it has been able to squeeze so much cognition out of nothing more than some artifacts, hearth scenes, and the like. While there are always more such discoveries to make, I would like to suggest that the recent move toward neuroscience is not of only passing interest to archaeologists but a necessary component of all of the human sciences, including archaeology. I believe that archaeologists have no choice but to triangulate, using archaeological and paleoethnographic evidence, paleoneurological evidence, contemporary human cognitive neuroscience and neuropsychology, and comparative primate cognitive neuroscience and neuropsychology. For only with all of them will we be able to home in on hypothesized ancestral psychological abilities and the neural pathways with which they were then probably correlated. We may then postulate on-

togenetic and phylogenetic neuroanatomical sequences to fill in the 2-million-year genotype gap.

This approach is painstaking, requiring a huge amount of contemporary and comparative data that are nowhere near complete and requiring also numerous inferences from those data sources to the archaeological evidence, each of which must be not only inductively supported by both sets of data but also deductively implied by, or at least consistent with, other data. Wynn and Coolidge's (2010) working-memory hypothesis demonstrates the richness of such an approach. Even if it turns out that working memory had little to do with past cognitive developments (which I think is most unlikely), they and those others who are now working along similar lines have shown that cognitive neuroscience can help us understand how we became who we now are.

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