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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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 postmorbid 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, purposive, 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; Furster 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 autonoetic 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. Rijsdijk, 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 archeological 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 archaeology 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 nonhumans, 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 handaxes 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 subgoals (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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