Working memory and working attention: What could possibly evolve?

Working Memory and Working Attention

What Could Possibly Evolve?

by C. Philip Beaman

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.

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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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 ± 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 (± 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 ± 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, Komarorva, 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.[1]

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).

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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 (Borsboom 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-

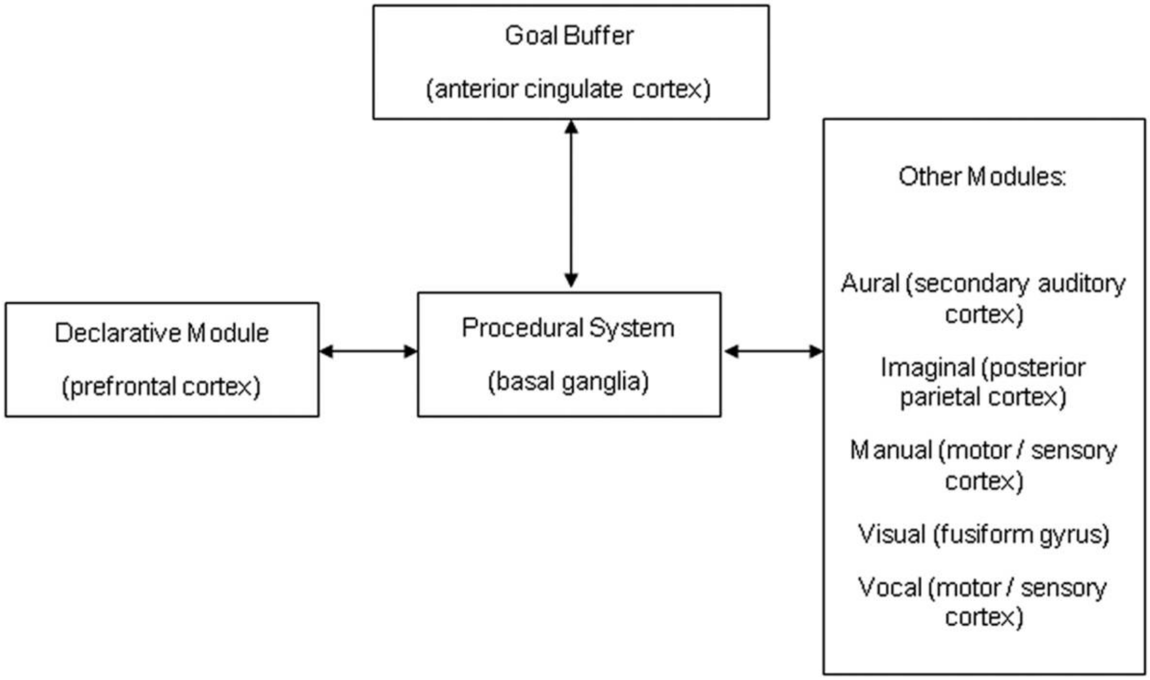

Figure 1. Adaptive control of thought-rational (ACT-R) model 6.0 (version from 2007). The core of the model is the relationship between the goal buffer (a kind of working memory in the sense of Miller, Galanter, and Pribram 1960), the declarative module, and the procedural system. Other modules that 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, Pullara, 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 nontrivial 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 subgoals 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 Oldowan 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 handaxes) 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 reinforced 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 personal 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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