Working Memory, its Executive Functions, and the Emergence of Modern Thinking

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This article examines the possible origins of modern thinking by evaluating the cognitive models of working memory, executive functions and their interrelationship. We propose that a genetic mutation affected neural networks in the prefrontal cortex approximately 60,000 to 130,000 years ago. Our review of cognitive and archaeological evidence yields two possibilities: either it was non-domain specific, affecting general working memory capacity and its executive functions, or the mutation was domain-specific, affecting phonological storage capacity. We discuss the sequelae of these possibilities for modernity, including language enhancement, greater reasoning, planning, and modelling abilities, and increases in fluid/general intelligence.

In 1848, 25-year-old Phineas Gage was the foreman of a railroad crew. He accidentally dropped a $13^1/_4$ pound iron-tamping rod on a dynamite charge. The resulting explosion drove the rod through the left side of his face and out the top portion of his skull. His attending physician wrote that '. . . his mind was radically changed, so decidedly that his friends and acquaintances said he was "no longer Gage"' (Harlow 1868, 340). As noted in a previous article (Coolidge & Wynn 2001), what has been missed in the recounting of Gage's tragic story is that the phrase 'he was no longer Gage' occurred in the context, not of his personality change *per se*, but in the loss of his previously acute business acumen and his energy and persistence 'in executing all his plans of actions' (Harlow 1868, 340). As such, we have previously noted that this passage may be the first in the literature to create the metaphor of 'executive functions' for the frontal lobes.

In our 2001 article, we also proposed a hypothesis in which the evolution of the executive functions of the frontal lobes was a key element in the evolution of modern human behaviour and culture. In the following article, we expand this hypothesis by subsuming executive functions under a well-established and powerful theory — Baddeley's (1993; 2000; 2001) concept of working memory. We suggest that an enhancement of working-memory capacity occurred in the relatively recent human past, most likely after the first appearance of anatomically modern humans, and that this development was the final piece in the evolution of human executive reasoning ability, language, and culture.

Executive functions

Modern concepts of executive functions are often traced to Luria (1966) who noted that patients with frontal-lobe damage frequently have their speech, motor abilities, and sensations intact, yet are often unable to carry out complex, purposive, and goal-directed actions. He also found that they could not accurately evaluate the success or failure of their behaviours and were unconcerned with their failures, and hesitant, indecisive, and indifferent to the loss of their critical self-awareness. Lezak (1982) also noted that frontal-lobe-damaged patients frequently lost their ability to be independent, constructive, creative, and socially productive and appropriate, despite their intact perceptual, language, and long-term memory abilities.

Pennington & Ozonoff (1996) defined executive functions as a unique domain of abilities that involves organization in space and time, selective

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inhibition, response preparation, goal-attainment, planning, and flexibility. They viewed the domain of executive functions as partially distinct yet overlapping with other cognitive domains such as sensation, perception, language, and long-term memory. Current neuropsychological assessment of executive functions also invariably includes measures of planning, sequential memory, and temporal-order memory (e.g. Lezak 1995).

Barkley (2001) approached the issue of defining executive functions from an evolutionary perspective. He viewed them as a biological adaptation resulting from interpersonal competition in groups. Barkley saw executive functions as a useful social self-defense against resource theft (including theft of spouses) and against interpersonal manipulation. He also saw them as advantageous in social exchanges (like reciprocal altruism or selfish cooperation) and useful in imitating and learning from others without the dangers inherent in trial and error. Barkley also proposed executive functions evolved in gradual stages over a period of at least a million years.

Gazzaniga *et al.* (2002) have emphasized that executive functions do not reside in a single structure but appear to result from the interplay of diverse cortical and subcortical neural systems. There are a number of models for the neurocircuitry and functionality of executive functions. Alexander *et al*. (1986) proposed five parallel but segregated frontal-subcortical circuits: two of these circuits are thought to be related to motor functions and to influence oculomotor and skeletal motor areas of the cortex. The three remaining circuits were the dorsolateral prefrontal cortex, the orbitofrontal prefrontal cortex (also known as the ventromedial prefrontal cortex), and the anterior cingulate cortex. Recently, Middleton & Strick (2001) presented evidence for two additional frontal-subcortical circuits and emphasized their interrelationships to subcortical structures, particularly the basal ganglia and the cerebellum. Much neuropsychological research has focused on the three frontal-subcortical circuits that are associated with the greatest neurological and behavioural repercussions from damage or dysfunction; the dorsolateral, ventromedial, and anterior cingulate cortices (e.g. Chow & Cummings 1999).

The dorsolateral circuit is generally associated with the classic executive functions, i.e. complex problem-solving, decision-making, verbal fluency, and some of the operations of working memory. The orbitofrontal prefrontal region is more closely connected to the limbic system and is associated with the regulation of emotions and social behaviour. Both systems are closely connected, and the prefrontal cortex in general has extensive projections to almost all regions of the temporal and parietal lobes, some projections to the occipital lobe, and to subcortical structures such as the basal ganglia, the cerebellum, and the brainstem. The gist of these interrelationships appears to be that the prefrontal cortex coordinates the processing of broad regions of the central nervous system. A third region of the prefrontal cortex is the anterior cingulate gyrus, which is thought to mediate motivational systems and action selection (Pennington 2002).

Damasio (1999) developed a 'somatic marker' hypothesis to explain the interrelationship of the orbitofrontal cortex, anterior cingulate gyrus, and amygdala and their contributions to decision-making (see also Bechara *et al.* 1999). Damasio believed that complex reasoning and emotion are intertwined with emotional valences. He noted that somatic markers rapidly narrow the options by automatically determining the affective consequences of each action. Damasio also hypothesized that humans first developed a core consciousness, that is, a coherent collection of neural information, which continually mapped the physical sources of information of the organism. He also deemed this core consciousness the beginnings of a proto-self. He proposed the later development of an autobiographical self which could create a record of past experiences of an individual. Damasio's hypothesis may reflect one aspect of a dual reasoning system as explicated recently by Carruthers (2002) and Stanovich (1999). This dual system will be addressed later.

Sarazin *et al.* (1998) speculated that cognitive executive functions may be associated with the metabolism of the dorsolateral prefrontal cortex, while affective executive functions involved with social interactions may be associated with metabolism of the orbitofrontal prefrontal cortex and related limbic systems. In support of these findings, Coolidge *et al.* (2004) have recently found evidence for a genetically-based comorbidity for executive function deficits and some chronic personality disorders. This latter issue may also be relevant to *theory of mind*, a term coined by Premack & Woodruff (1978). It refers to the ability to represent mentally and infer unobservable mental states in others such as desires, intentions, and beliefs. Theory of mind deficits have been found in some individuals with known executive function deficits, e.g. autistic disorder (Pennington 2002). Theory of mind appears to require fully functioning prefrontal cortex and frontal lobes (Shallice 2001; Stuss *et al.* 2001).

The marriage of executive functions and working memory

Once upon a time there was short-term memory: an acoustic, temporary, limited capacity verbal store. Yet little did cognitive psychologists realize the ultimate impact that Baddeley's (Baddeley & Hitch 1974) revision of the concept of short-term memory was to have on the field of brain and memory research. Over the past decade, it may be the single most provocative and intensely-researched model in the field of cognition. Historically, short-term memory was typically measured by a simple digit span task, where subjects were asked to repeat varying series of numbers. Baddeley & Hitch expanded upon this notion by proposing a tripartite working memory model that included an attentional panmodal controller or central executive, and two slave systems, the phonological loop and the visuospatial sketchpad.

The phonological loop contains two elements, short-term phonological storage of sounds and an articulatory loop that maintains and rehearses information either vocally or subvocally. Baddeley viewed its primary purpose as evolving for language acquisition and comprehension. The visuospatial store was hypothesized to involve the maintenance and integration of visual ('what' information, like objects) and spatial ('where' information, like location in space) elements and a means of refreshing it by rehearsal.

The central executive: an emergent property

With some modifications, Baddeley and others (e.g. Baddeley & Logie 1999; Miyake & Shah 1999) currently view the central executive either as 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 slave systems. Some brain-function models have relegated working memory (primarily phonological storage) to being simply a subcomponent of the various functions of the prefrontal cortex. However, with a raft of new evidence from empirical studies (for a review of contemporary working memory models and empirical evidence see Miyake & Shah 1999), it may be more parsimonious to view Baddeley's working-memory model as having subsumed the traditionally-defined aspects of executive functions. 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'.

One provocative part of the tripartite working-memory model is the concept of the central processor or executive. Baddeley adopted an attentional control system, called the Supervisory Attentional System (SAS) originally proposed by Norman & Shallice (1980), as the basis for his central executive. Gazzaniga *et al.* (2002) recently attributed its attentional functions primarily to the anterior cingulate gyrus. The SAS takes control when novel tasks are introduced, when pre-existing habits have to be overridden, or when danger threatens and task-relevant decisions must be made.

More recently, Kane & Engle (2002) have also given Baddeley's central executive a neural basis (primarily the prefrontal cortex), 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, whose chief function is the active maintenance of appropriate stimulus representations relevant to goal attainment in the face of interference-rich contexts. Collette & Van der Linden (2002) have also postulated, from 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.

The theoretical status of Baddeley's central executive as a single unit is not without criticism. He admits that multiple segregated information-processing modules may ultimately replace his notion of a single central executive controlling system. Interestingly, Goldman-Rakic (1995) noted that while current evidence favoured multiple working-memory domains, the idea of a central panmodal executive processor could not be completely dismissed. She stated that the human brain may have a genuine cortical centre, oblivious to informational domains. She speculated that future studies may reveal the location of this area (or network) but noted that they have not thus far. It has also been argued (e.g. Miyake & Shah 1999) that the notion of a central executive still begs the question of a homunculus (Baddeley freely admits the problem of the homunculus in his model: Baddeley 2001), and it is an unanswered question in most current working-memory models.

In a factor-analytic study of executive functions, Miyake *et al*. (2000) identified three factors as fundamental to executive functioning: mental set shifting, inhibition of prepotent responses, and information updating. Oberauer *et al.* (2003) proposed that working memory could be differentiated into two facets: one, the content domains (akin to Baddeley's phonological store and the visuo-spatial sketchpad) and the other related to its cognitive functions (Baddeley's executive functions). Oberauer *et al*., in a statistical analysis of 30 working-memory tasks, found three meta-working memory functions: simultaneous storage and processing, supervision (i.e. executive functions of the central executive), and coordination of elements into structures. Of course, all factor-analytic studies' outcomes are completely dependent on the initial set of variables. The previous studies' differing conclusions show the highly-complex yet highly-interrelated nature of working memory and its executive functions.

Whether the central executive is a unitary or nonunitary concept we may still ask where, how, and why does it make its decisions? Miyake & Shah (1999) have proposed that the attention and decision-making qualities of the central executive may be an emergent property, that is, they arise as a function of the dynamic interplay of the multiple and interrelated systems associated with working memory, including the two slave systems, the multiple long-term memory systems and their cortical and subcortical connections. We would assume its ability to maintain appropriate attention and to make decisions would have been favoured by natural selection. Certainly, the ability to attend to relevant stimuli, and filter out irrelevant stimuli, and the ability to make quick and efficient decisions would have been favoured over static processes. Support for the decision-making nature of the central executive also comes from Frankish (1998a,b) who has speculated that it is an innate predisposition of human consciousness to accept, reject, or act on propositions. He postulates a 'super mind' constituted by higher-order decision-making (as cited in Carruthers 2002). These propositions are framed by language most often through inner speech or subvocalization, which are aspects of phonological storage.

A fourth function that Baddeley (2000; 2001) recently attributed to the central executive is the episodic buffer, a short-term multimodal mnemonic interface between working-memory systems and long-term memory. He conceives of the episodic buffer as purely mnemonic in character and the central executive as purely an attentional system but whose role may extend beyond memory function. He leaves vague whether conscious awareness is a defining characteristic of the central executive, but he proposes that retrieval from the episodic buffer into awareness allows multiple sources of information to be compared and contrasted simultaneously. He hypothesizes that this action allows sophisticated problem-solving and the planning of future behaviour.

Baddeley's episodic buffer hypothesis has received some criticism. First, it is less parsimonious than other models (e.g. Cowan 1995; 1999; Ericsson & Kintsch 1995) that postulate that working-memory buffers are merely activated portions of a long-term memory system. More recently, Ruchkin *et al.* (2003) have presented electrophysiological evidence that the activation of representations in long-term memory, involving prefrontal cortex and posterior cortical systems, is the representational basis for working memory, and they see no need to posit specialized neural networks such as Baddeley's episodic buffer. A summary of Baddeley's model, modified by the present authors, appears in Figure 1.

Executive attention, working-memory capacity, and fluid intelligence

Kane & Engle (2000; 2002) and Engle *et al.* (1999) have defined executive attention as the ability to maintain memory representations in a highly-active (conscious) state despite interference or response competition. These representations may consist of plans of action, short- or long-term goals, or task-relevant stimuli. They noted that a critical aspect is the ability to maintain this information despite interference. It is critical because plans, goals, and tasks are more easily retrieved from long-term memory when no interference is present than when it is present. They also postulate that there are individual differences in this capability, which they label as working-memory capacity. The active maintenance of information and the ability to block distractors are highly-interdependent features of executive attention that form the basis of working-memory capacity. Furthermore, they hypothesize that these control functions of working-memory capacity link it to higher-order cognitive abilities. They also review the mounting evidence that working memory and executive functions are subserved by the dorsolateral prefrontal cortex (with other extensive cortical and subcortical connections).

Interestingly, their research (and others, e.g. Kyllonen 1996) has provided support that indi-

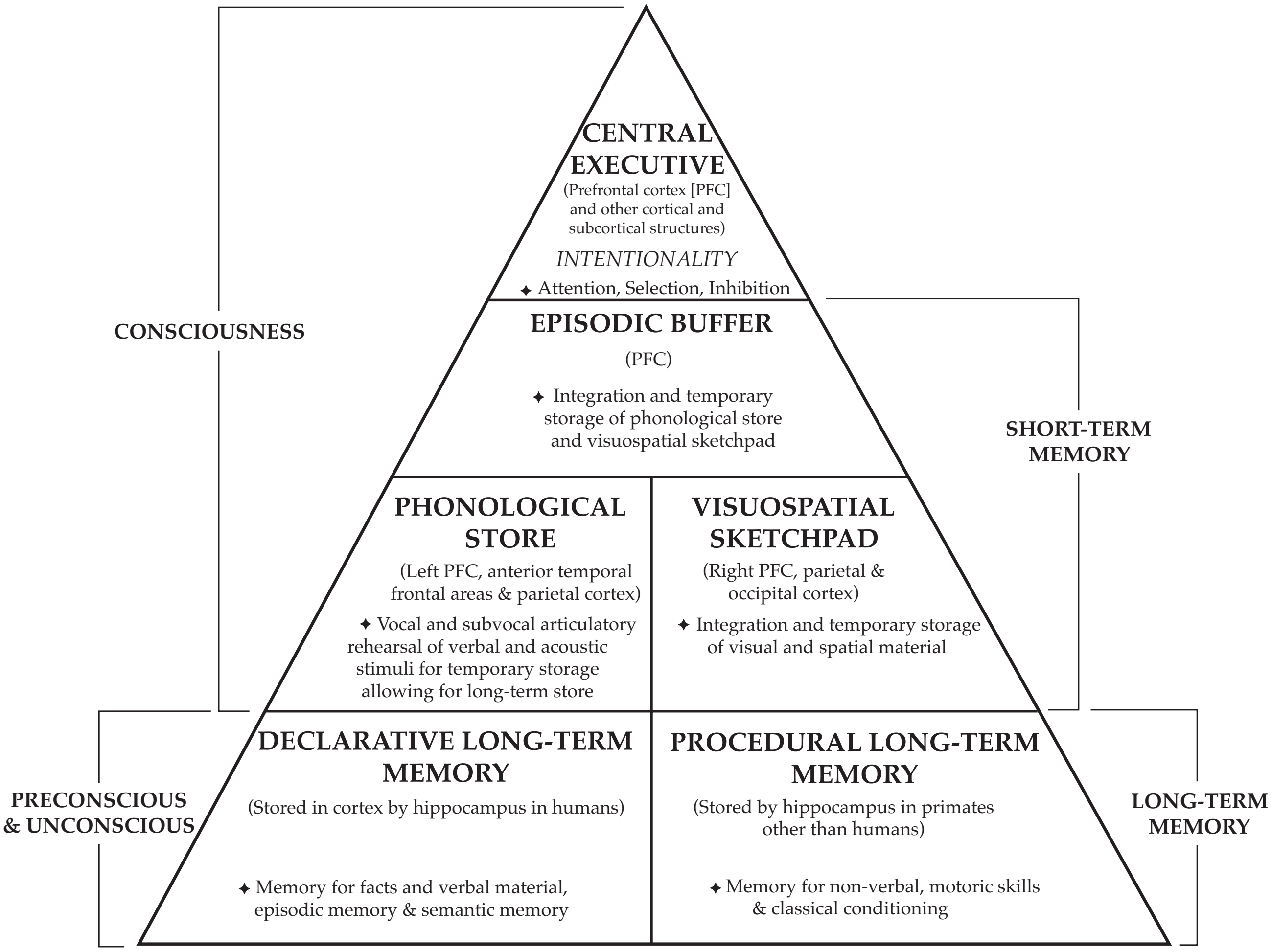

Figure 1. *A revision of Baddeley's working-memory model.*

vidual differences in working-memory capacity may be related to general intelligence (also known as Spearman's g) and more specifically, fluid intelligence (Cattell's gF). This latter aspect of intelligence is thought to be the ability to solve novel problems and depends less on schooling and acculturation than crystallized intelligence, gC, which is more dependent on formal schooling and acculturation. They also note that working-memory capacity (or central executive attention) is a domain-free process. This implies that any specific task would require the use of some domain-specific stimuli, processing, and skills in conjunction with working-memory capacity. Thus, no single neuropsychological measure can exclusively capture the executive component of working-memory capacity, and each test or battery of tests would tap both the domain-free working-memory capacity and the domain-specific skill required.

Phonological loop

The phonological loop is of particular interest in regard to more sophisticated language use. Baddeley hypothesized that the phonological loop has two components: brief-speech-based storage that fades within about two seconds, and an articulatory control processor. The latter processor maintains material in the phonological store by vocal or subvocal rehearsal. It was also assumed that spoken information gains automatic and obligatory access to phonological storage. Baddeley hypothesized that the phonological store evolved principally for the demands and acquisition of language. More recently, Baddeley (2001) has hinted that the phonological loop may even be more important to the attentional and decision-making aspects of the central executive than he previously thought. He stated that recent evidence 'had the positive effect of alerting my colleagues and me to the potential importance of the phonological loop in controlling action . . .' (Baddely 2001, 856).

In the laboratory, phonological storage has been traditionally measured by the digit-span task, a subtest of the Wechsler Adult Intelligence Scale. Interestingly, the digit-span task has been shown to be strongly heritable (e.g. 56 per cent of its variance may be due to additive genetic influences: Rijsdijk *et al.* 2002). A more recent measure of phonological storage (also termed verbal working memory), developed by Shah & Miyake (1996), has also been shown to be highly heritable with an additive genetic influence varying from 35 per cent to 51 per cent (Ando *et al*. 2002). Additionally, Ando *et al*. found their measures of executive functions and visual spatial storage were also heritable (37 per cent to 57 per cent). Coolidge *et al.* (2000), in a study of child and adolescent twins, found that a core of executive functions, consisting of planning, organizing, and goal attainment, was highly heritable (77 per cent) and the core functions were found to be attributable to as few as four pairs of alleles. Finally, Hansell *et al*. (2001), using event-related potential slow-wave measures of working memory in a visual-spatial delayed-response task, showed strong heritability (35 per cent to 52 per cent) in a sample of 391 adolescent twin pairs. The neural location of the phonological store appears to be the inferior parietal lobe of the speech-dominant hemisphere (Becker *et al*. 1999) and anterior temporal frontal-cortex areas (Gathercole *et al.* 2004).

As noted earlier, the visuospatial sketchpad holds and maintains visual ('what' information, like objects) and spatial information ('where' information, like location in space). There is also evidence that these may be relatively separate systems, one for the memory of visual patterns and another for the memory of spatial locations and the memory for sequences of movements. The latter ability, often called procedural memory, has been linked to systems of the posterior portions of the frontal lobes and the perceptual motor cortex. These areas are involved in the formation, storage, and retrieval of memories for motor procedures like juggling. These memories tend to be formed more slowly, taking many repeated trials. The relationship of visual imagery to spatial working memory has not been fully determined (e.g. Baddeley & Logie 1999). Evidence clearly suggests, however, that verbal and spatial working-memory capacities are relatively separate systems, that is, they may interact but might rely on different neural substrates. It may also be proposed that, evolutionarily, the visuospatial sketchpad may be the older of the two systems. Certainly, early stone-knapping techniques like Levallois suggest complex motor skills and procedural memory. The development of the phonological store, however, may have allowed greater representational and storage capacity for the visuospatial sketchpad as well as the ultimate integration of the two. The neural location for spatial short-term memory (a component of the visuospatial sketchpad) appears to be the non-dominant speech hemisphere and inferior frontal and occipital cortex (Smith & Jonides 1997).

Rossano (2003) has recently proposed that the deliberate practice required in becoming a skilled stone tool-knapper may have served as one of the original bases for consciousness. He reasoned that deliberate practice requires evaluation of one's performance against a more proficient model. This self-monitoring process would require goal-setting, voluntary control over actions, and error-detection and correction. It would also require the recall from long-term memory of hierarchically-organized retrieval structures that have been previously demonstrated to be useful to the task at hand, which we shall now address.

Working memory and long-term memory

There are many models and dichotomies for long-term memory such as explicit and implicit, direct and indirect, declarative and procedural, semantic and episodic, source memory, recency memory, and others. To some extent explicit, direct, declarative, and semantic long-term memories overlap. They are names for memories of facts, names for things, and are often verbal (but not exclusively). The hippocampus appears to be essential for their transference to long-term storage in other cerebral locations. It is a conscious process by which the name for something is vocalized or subvocalized through phonological storage, and then relegated to long-term memory by way of the hippocampus if that thought has been repeated enough or has a particularly strong emotional valence. The hippocampus is not the place of storage but the site that forms the memory traces that are stored elsewhere and the site where long-term memories are retrieved and passed to working memory, i.e. where we become aware of a memory and can vocalize it. Declarative memories tend to be predominant in the hippocampus and the phonological loop.

Implicit, indirect, and procedural memories are largely unconscious, automatic, often non-verbal, and apparently do not require an intact hippocampus in order to be relegated to long-term memory. Learned motor skills (like juggling and, perhaps, basic stone knapping) and cognitive skills, priming, and classically-conditioned responses are examples of implicit, indirect, or procedural memories. Their operations are not directly consciously accessible, and thus, as we noted earlier, may be part of a much older memory system in our evolutionary history.

Episodic, source, and recency memories are the conscious recollections of our personal experiences. They may be encoded consciously or unconsciously and, again, the emotional valence of the experience will affect the strength of the encoding and its subsequent retrieval. Baddeley proposed that it was the nature of episodic memory to allow for associations to form naturally between related events. An episodic learning mechanism would form rapid links between things formed at the same time. This would allow one link in an episode to evoke another link in the same episode, thus forming a complete episodic memory. Source and recency memory (e.g. Milner 1995) allows for the organization and segregation of these items and links in time, and these processes are strongly disrupted by damage to the prefrontal cortex. It is debatable whether semantic memories are just shortened episodic memories; that is, in Baddeley's conception of them, whether semantic memories are episodic memories with far fewer links or whose source or recency information has been lost or forgotten (e.g. Gazzaniga *et al.* 2002).

Whether the working-memory stores constitute a separate anatomical and functional system from long-term memory or whether they are activated parts of long-term-memory is debatable (Miyake & Shah 1999; Ruchkin *et al.* 2003). Nevertheless, long-term memory storage and retrieval is an integral part of working memory. O'Reilly *et al.* (1999) have theorized that the primary role of the prefrontal cortex is the active maintenance of information which is self-regulated and dynamically updated, akin to Baddeley's central executive, and they also propose that it arises as an emergent property. The hippocampal system serves to form, store, and retrieve relevant declarative memories. They postulate that this system tends to be more rapid than the posterior and perceptual motor cortex, which is involved in the formation, storage, and retrieval of implicit and procedural memories. The latter tend to be formed more slowly (as in the development of a good backhand in tennis) although there are exceptions (one-trial learning in classical conditioning). Once formed, however, they may be highly resistant to interference and extinction. They view knowledge as the encoded synaptic weights between neurons (Baddeley's links) that are relatively stable over time. They define learning as the modification of the encoded weights between neurons through repetition. The controlled processing of the prefrontal cortex maintains constraints (goal, task-at-hand, environmental restrictions) and retrieves appropriate knowledge consonant with these constraints. In their view, part of the controlling mechanism is attention, which in part is the ability to inhibit irrelevant stimuli. They also emphasize the importance of the phonological loop in the maintenance of relevant stimuli. They view language as an exceptionally powerful representational system for encoding verbal and non-verbal information as well as abstract spatial and numerical information. It is also important to note that O'Reilly *et al.* postulate that all of the working-memory mechanisms are highly likely to be genetically based. Their latter contention has received strong recent support as noted previously.

Working memory and language

Two recent genetic studies have provided preliminary evidence that a single gene and its alteration may have had a profound effect upon language comprehension and production. It is well accepted that speech and language development are genetically influenced (e.g. Jackendoff 2002; Plomin *et al.* 1997). Recently, Lai *et al.* (2001) found that a single gene (known as FOXP2) might also have a profound and deleterious effect upon the developmental process that culminates in speech and language. They were able to identify this gene in a three-generation pedigree and in an unrelated individual with similar articulation, linguistic, and grammatical impairments. There is still debate, however, about whether this gene affects a more general or hierarchical brain function or whether it is a gene specific to language disabilities. Enard *et al.* (2002) recently determined that two functional copies of FOXP2 appear to be required for the acquisition of normal spoken language. They also sequenced the complementary DNAs that encode FOXP2 in different primates and compared them to humans. They surmised that this gene has been the target of natural selection during recent human evolution, beginning approximately 200,000 years ago. Again, however, whether the gene is highly specific to language or controls more general developmental neural processes is yet to be determined.

Support for a mutation in the anthropological literature

There are some current anthropological constructs that support our hypothesis for a genetic mutation in the executive functions of working memory and its effects upon language development. Anthropologists have long recognized that understanding the neural basis for cognition is important to understanding the evolution of behaviour and culture (e.g. Holloway 1969; Parker & Gibson 1979). Some have even drawn specific attention to abilities linked to the frontal lobes (e.g. Marshack 1985). Our review will confine itself to three recent sources, Mithen (1994; 1996), Ambrose (2001), and Klein & Edgar (2002).

Mithen (1996) proposed three phases for the evolution of the mind: first, the period when minds were dominated by a domain of general intelligence; second, the period when general intelligence was supplemented by multiple yet segregated specialized intelligences (and probably more typical of archaic *Homo sapiens* like Neanderthals); and third, the current phase where multiple specialized intelligences work together with a flow of knowledge and ideas between behavioural domains (typical of modern humans). He labelled the latter process 'cognitive fluidity', which he thought was a greater accessibility between specialized intelligences. Mithen also postulated that the latter two phases may parallel two levels of consciousness: a lower level with awareness of bodily sensations and external perceptual stimuli, and a higher level of consciousness which allows a reflection of one's own mental states. Mithen suspected that Neanderthals lacked this higher level of consciousness and endorsed Dennett's (1991) vision of a rolling consciousness with swift memory loss and no introspection as characteristic of Neanderthals. Mithen, however, did not link his intelligences to specific neural substrates nor did he specify its cause as genetically determined. He also thought the development of cognitive fluidity reflected 'new connections' without an increase in brain size. (See our recent articles for the application of our model to Neanderthal thinking: Wynn & Coolidge 2004; Neanderthal culture: Coolidge & Wynn 2004; and foraging: Wynn & Coolidge 2003.)

There is some consensus that an explosion of culture began approximately 50,000 years ago. Art, personal ornamentation, symbolism, technological advances in tool making, artefacts made from materials other than stone, land-use planning, resource exploitation, strategic social alliances, evidence for religion, and highly-ritualized burial all became rules rather than exceptions in the archaeological record (see also Bar-Yosef 2002; Klein 2000; Mellars 1989). Mithen proposed that these cultural changes were consequences of the change in thinking and not the cause of the change in thinking. As for the nature of his accessibility mechanism, he cited the work of Gardner (1983) who believed that the modern mind slowly or suddenly linked together separate domains, and subsequently executed complex human activities in a seamless manner.

Ambrose (2001) hypothesized that the beginnings of composite tool-making, about 300,000 years ago, reflected an increase in cognitive capacity. He reasoned that composite tool-making requires the planning and coordination of multiple segregated tasks. He postulated that these coordinated planning behaviours coevolved with a frontal lobe parallel-processing module in the frontopolar prefrontal cortex (FPPC). Support for his contention comes from an fMRI study (Koechlin *et al.* 1999) that demonstrated the FPPC selectively mediates the human ability to keep primary goals in mind while evaluating secondary goals, which are essential aspects of planning and reasoning. Additional fMRI evidence for the role of the prefrontal cortex in planning and reasoning activities is provided by a study by McCabe *et al*. (2001) who found that activation of the prefrontal cortex occurred most strongly in human adult subjects who cooperated with other humans in games requiring trust and reciprocity.

Klein & Edgar postulated that a 'fortuitous mutation' (2002, 270) caused a neural reorganization that resulted in the purported explosion of culture approximately 50,000 years ago. Although they also did not specify the nature of the neural substrate involved, they did hypothesize that rapidly-spoken phonetic speech might have been a part or consequence of the genetic neural change. They further reasoned that an expansion of language would allow for mental modelling and the creation of 'what if' questions. They cautioned that this was not to say that Neanderthals and their contemporaries were primitive and possessed ape-like brains but that some genetic mutation in modern *Homo sapiens* did have some extraordinary behavioural repercussions.

Of course, the palaeoanthropological record leaves no evidence of soft neural tissue organization or direct measures of behavioural change. Despite this inherent problem, it is possible to match many of the behavioural features of working memory and its executive functions with activities reconstructable from archaeological evidence. At this point in our presentation, we will speculate as to the specific nature of this genetic mutation.

Enhanced working memory

We think it important to view the multiplicity of executive functions of working memory as under the auspices and control of a central executive. We have already presented evidence that this complex system results from the interplay of multiple neural systems and circuitries and the gradual evolution of these functions and systems over millions of years. As Barkley (2001) has already noted, it may be best to conceive of their development in gradual waves over a long period of time. Thus, 500,000 to 400,000 years ago, there certainly must have existed some earlier core executive functions of working memory. These less powerful executive functions might have included limited planning, organizational skills, and decision-making. The making and use of the Schoeningen spears may be a reflection of these earlier executive functions. Thieme (1997) speculated that the hunters who used these spears may have ambushed horses, driven them into the water, and killed them with the spears. Although this interpretation remains controversial, at the least, it demonstrates some planning and decision-making abilities well beyond simple scavenging, and at best, it may demonstrate more sophisticated executive functions. Regardless, we view the Schoeningen spears as preliminary evidence for early executive functions.

Based on earlier empirical work indicating that the core of executive functions might be controlled by as few as four pairs of alleles (Coolidge *et al.* 2000), we hypothesize that a single additive genetic mutation occurred in working memory and that the mutation might have increased working memory capacity. We refer to this dramatic change as enhanced working memory (EWM). We also assume that EWM was exapted (Gould & Vrba 1982) by language. (Note: there are no known single genes that account for a significant proportion of variance of individual differences for any complex human behaviour. Therefore, most genetic influences upon behaviour are said to be additive, i.e. a confluence of specific genes that contributes to a particular behaviour. However, each gene's influence in a confluence may differ, although they are often assumed to be of equal weight: Plomin *et al*. 1997).

As to the specific nature of the change in EWM, we envision two possibilities: one is that the mutation occurred in the non-domain-specific capacity of working memory (one of its executive functions or the episodic buffer), and the second is that it was a domain-specific mutation in one of the slave subsystems of working memory (phonological store or visuospatial sketchpad).

We see support for the non-domain-specific working memory mutation in the work of Russell (1996) who drew parallels between the development of symbolic thought in children and the evidence for symbolic behaviour in the archaeological record (40,000 to 30,000 years ago) in a Piagetian framework. He argued that the essence of symbolic representation is the ability to 'hold in mind' some representation that is not what is currently 'held in view', and he defined this broad ability as working memory, 'memory for the future', or ' prospective memory'. Russell presented evidence for the neural location of this ability as the prefrontal cortex. He proposed that modern humans' larger working-memory capacity was a necessary precondition for symbolic thought, although he did not think it was a sufficient one. Russell speculated that selective pressures contributed to the 'growth' of working memory but did not specify them. He furthermore speculated that a capacity for holding in mind would also support the linguistic function of predication, that is, qualifying words about a referent that allow the referent to be identified by the addressee (e.g. the *green* rock). Thus, he saw working memory as a candidate for being the principal non-social and non-linguistic factor in the evolution of human symbolic thought, and he hypothesized that the neural substrate for this working memory existed for at least 50,000 years before it came to be used for symbolic ends. According to Russell, this would place the cognitive neural substrate required for modern symbolic thought in anatomically modern humans about 100,000 years ago.

Russell's description of symbolic thought via working memory is consistent with Kane & Engle's (2002) definition of working-memory capacity. They saw working-memory capacity as the active maintenance of information (Russell's 'held in view') consonant with a representation or goal (Russell's 'hold in mind') and the ability to block them both from distractors or interference. Such an increase in ability undoubtedly would have been a boon to language. Indeed, the novel reorganization in working memory may have been exapted from language. Ultimately, it may be difficult to tease out an answer. At the very least, however, it seems highly likely that the mutation occurred in one of these two systems or was highly related to both of them.

As noted earlier, a second possibility for a mutation in working memory is that it was domain-specific, in one of the two slave subsystems. Our candidate would be that a mutation increased phonological storage capacity. As Baddeley & Logie have noted (1999) the phonological loop might be considered a major bottleneck in the process of language comprehension, and it would certainly be a bottleneck in language production. A relatively simple mutation that increased the length of phonological storage would ultimately affect general working-memory capacity and language. Increased phonological storage might have changed pre-modern *Homo sapiens* from rolling consciousness with swift memory loss to the higher-level consciousness that Mithen (1996) has proposed. Increased phonological storage would have allowed greater articulatory rehearsal, consequently allowing for automatic long-term storage, and the beginnings of introspection and self-reflection (and thus, the beginnings of consciousness). Greater phonological storage would have allowed increases in syntactical complexity. Sentences might not only be longer and contain more information, but they could also be imbued with more meaning through syntactical embedding, thus containing more information, resulting in enhanced reproductive fitness. A greater phonological store might also permit greater morphemological richness. While the native ability to produce different morphemes might not have been directly affected, the ability to hold and maintain new and various combinations of morphemes might have been enhanced by an increase in phonological storage. Increased phonological-storage capacity might also have allowed greater verbal fluency and the comprehension of rapidly spoken speech.

Baddeley *et al.* (1998) reviewed the empirical evidence for the importance of the length of the phonological loop in digit span, familiar word repetition, and non-word learning. They created two groups of children based on their ability to repeat lists of nonwords but matched them on their non-verbal memory. They found that children who were poorer at nonword repetition were also poorer at new-word learning (presumably because of a smaller phonological-memory capacity). They concluded from this and other studies that in spite of its limited capacity, the phonological loop is important in the construction of more permanent representations of the phonological representation of new words. Given that language learning is critical to cognitive development and thinking, the importance of the phonological loop cannot, perhaps, be overstated.

The increase in phonological-storage capacity might also have affected the pragmatics of speech, like the enhancement of modes of speech. For example, simple declarative sentences could now contain more information. Commands (imperative mode) could become more complex. Questions (interrogative mode) could contain more specific information as well, and the results might have been greater efficiency, clarity, and more effective communication.

An increase in phonological-storage capacity might have allowed for the creation and enhancement of the subjunctive mode of speech (Klein & Edgar's 'what if' statements) or the development of the future tense. In part, because of its highly transient nature, working memory would not necessarily benefit from memories of the past stored in long-term memory. So how would greater phonological storage aid the prediction of the future? Baddeley proposed that working memory would allow for the reflection and comparison of multiple past experiences. This might allow the organism actively to choose a future action or create an alternative action, rather than simply choosing the highest path of probable success. Although an organism would still be better off (compared to one without benefit of past experience) choosing alternatives simply based on the past, Baddeley proposed that working memory would allow for the formulation of mental models of future behaviour.

Shepard (1997) comes close to describing this same working-memory and long-term memory dichotomy. He postulated that natural selection favoured a perceptual and representational system able to provide implicit knowledge of the pervasive and enduring properties of the environment (long-term memory) and that natural selection also favoured a heightened degree of voluntary access to this representational system (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 (as in Baddeley's semantic memory or Mithen's natural-history intelligence or technical intelligence) would not result in advances in scientific human knowledge but its advancement would 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. Dawkins (1989) also proposed that natural selection would have favoured the reproductive success of those organisms capable of simulation. He described systems highly similar to those of executive functions and replete with the executive functions metaphor. For example, he viewed consciousness as the culmination of an evolutionary trend where consciousness served as an executive decision-maker with the acquired 'ability to predict the future and act accordingly' (see also discussions in Mithen 1998).

Sugiyama (2001) has recently argued that narratives, folklore, or story-telling (all of which may be clearly categorized as episodic memories) may have been naturally selected for because of their efficiency and safety in the acquisition of information. Verbal representations are substitutes for time-consuming and sometimes dangerous first-hand experience. She posits that fitness in varying habitats may particularly have aided foraging knowledge by transmitting information about geography, plants, fauna, weather, and other aspects. It may be surmised that increased phonological storage would serve to create and store more elaborate stories (and thus contain greater information) and serve as a better and larger 'stage' for their recall from long-term memory.

Increased phonological storage as an aid in cross-modal thinking

An increase in phonological storage could have also aided in cross-modal thinking. Hermer & Spelke (1996) found that young, pre-linguistic children rely highly on geometric information when disoriented in a room. It seems they are not capable of integrating geometrical and non-geometrical information when searching for a hidden object. Success in the task is not dependent on IQ, age or vocabulary size. The only successful predictor was the conjoint use of spatial vocabulary with non-geometric information in a single thought or memory (e.g. 'it's to the right of the blue one'). Hermer-Vasquez *et al.* (1999) were also able to replicate this finding in adults in a related but different task. As a whole, the findings support Carruthers's (2002) contention that language serves as the vehicle of inter-modular thinking, and we contend that increased phonological storage allowed language to 'load up' additional information in a single spoken or subvocalized thought that gave *Homo sapiens sapiens* its ultimate selective advantage.

Gathercole *et al*. (2004) found that increases in memory capacity as children grow older may be due to increased rates of rehearsal (articulatory processor). In younger children (less than 7 years), where spontaneous rehearsal is rare, the phonological loop may consist only of the phonological store. Older children not only rely on articulation as a storage mechanism but also recode visual inputs into a phonological form through the articulatory processor. Thus another candidate for our proposed mutation may have been the articulatory control processor.

Mutation timeline

It may be that those who came out of Africa approximately 130,000 to 100,000 years ago already had EWM. Indeed, it may have allowed and promoted the ultimate success of their emigration. Admittedly, there is little evidence for major behavioural differences between anatomically modern *Homo sapiens* and other human types at this time period. There are, however, tantalizing fragments of earlier evidence. For example, White *et al.* (2003) recently found what they claim to be an ancestor of anatomically modern *Homo sapiens* in Herto, Middle Awash, Ethiopia, which appear to date between 160,000 and 154,000 years ago. They found that three of the primary crania all bore indications of some kind of cultural modification, perhaps associated with mortuary practices. Since 15 of 24 recovered fragments showed intensive bone modification and because these modifications are not consistent with remains processed for consumption, the authors concluded that it was unlikely to represent utilitarian or economic behaviour, i.e. it may have been symbolic.

A second scenario is that the mutation occurred after the initial emigration of anatomically modern *Homo sapiens* out of Africa but before the time of the purported cultural explosion. Certainly, the behavioural effects of a genetic mutation do not sweep through a population in less than a couple of generations. This may be particularly true if the behavioural consequences of such a mutation arose in segregated locations or across continents. Shea (2003) proposes that the speed with which modern humans practising Upper Palaeolithic adaptations penetrated Neanderthals habitats in Europe suggests that these strategies may have been first honed in the Levant approximately 140,000 to 70,000 years ago. Thus, we are proposing a broad time band, perhaps as distant as 160,000 years ago or greater, or as recent as 70,000 years ago or earlier, which will be addressed again later in the article.

The archaeological record

Thus far we have made a case for the importance of enhanced working memory (EWM) in modern cognition, its linkage to recognized neural structures, and its relatively simple genetic basis. Some evolutionary psychological arguments would end here, and account for the evolution of EWM in terms of its obvious advantage in the environment of evolutionary adaptedness (Bock & Cardew 1997). We aver, however, that to make a compelling case for the evolutionary significance of EWM (or any characteristic for that matter) it is also necessary to document its appearance in the palaeoanthropological record. This would allow identification of the actual context of its evolution — surely a scenario preferable to imagining features of the environment of evolutionary adaptiveness.

Enhanced working memory is admittedly difficult to recognize in the palaeoanthropological record, but not impossible. Fossils are little help. The neural changes associated with EWM leave no recognizable landmarks on the gross anatomy of the brain, so even a superbly-preserved endocast would fail to reveal EWM. The geographic location of a fossil can be informative, but only if it is found in a place (e.g. an oceanic island) that would be difficult for people to reach without the complex contingency plans enabled by EWM. We must therefore rely primarily upon the archaeological record, which preserves traces of human action. Some domains of cognition can be accurately preserved in the archaeological record — spatial cognition is one good example (Wynn 1979; 1989; 2002), and the expert memory used in technological tasks is another (Wynn & Coolidge 2004). But EWM leaves few direct clues. There are two reasons for this. First, EWM is not a qualitative characteristic; it was an enhancement of an ability possessed by earlier hominids, and such quantitative changes are much harder to recognize. Second, EWM is unnecessary for most of the activities that leave archaeological traces. Mundane, day-to-day activities rarely call upon the full resources of working memory. Making tools, finding and preparing food, socializing, and so on can all be accomplished without the expanded attention capacity of EWM. This is true even for people living in modern industrialized societies. As a consequence, most of the activities documented in the archaeological record preserve no clues for EWM. But the situation is not hopeless. Some patterns do imply the presence of EWM, and when considered in aggregate, these present a provocative, but not uncontroversial, picture of the evolution of EWM.

Here we focus on four abilities that rely on EWM, and which have the potential to leave traces in the archaeological record. The first is group contingency planning, where potential errors are specifically identified, and alternatives conceived and discussed. Most planned activities do not qualify, because most day-to-day planning can be handled quite effectively by learned tactics held in long-term memory (Wynn & Coolidge 2004). Second are innovative plans of action, in which people devise entirely new solutions to problems, as opposed to simply varying a response within a range of known solutions. Innovations are often created through the simultaneous processing (e.g. comparison) of a variety of disparate information (see previous discussion of Shepard). Third is temporally-remote action. This is not simply the anticipation or recollection of an event, but the organization of sets of actions to be performed at a remote point in time or space. Fourth is evidence for the use of cultural algorithms, which are sets of rules that themselves streamline problem-solving. All of these require the phonological store of working memory to encode, hold in attention, and relay the complex interrelationships. These complex activities can leave archaeological traces; some of these traces are quite convincing, others less so. We divide the evidence into four categories: technology, foraging systems, information-processing systems, and one provocative case.

Technology

Tool-use and tool-making appear to engage the visuospatial sketchpad of working memory more than they engage the phonological loop. The unfortunate consequence of this is that technical activities, while the most common variety of archaeological evidence, are least likely to require the most enhanced version of working memory. Work by cognitive anthropologists has documented the largely non-verbal nature of technical activity and technical learning (Gatewood 1985; Keller & Keller 1996; Gardner 2002). The non-verbal nature of technical activity is why apprenticeship is so essential, and why 'how-to' books are of little use to the complete novice. Tool use relies heavily on muscle, aural, and visual imagery, and also on procedural memories that have been internalized by repetition. Visuospatial sketchpad is the key to this kind of planning. It is not that the phonological loop is never deployed, but it is of secondary importance, and may not be necessary at all. Indeed, there are reasons for thinking that the visuospatial sketchpad has been 'modern' for several hundred thousand years. Early stone-knapping techniques like Levallois (Wynn & Coolidge 2004), and early stone tool types such as twisted profile handaxes appeared at least 300,000 years ago, and would appear to require a complexity of images held in the visuospatial sketchpad of working memory (Wynn 2002). No more complex form of stone knapping *ever* appears.

Despite the primary involvement of the visuospatial sketchpad in technical activities, technology is not entirely mute when it comes to working memory. There are, in fact, some technologies that may provide evidence for remote action and contingency planning, which employ the phonological loop and the central executive. The modern world is replete with technologies that would provide solid evidence for EWM; the difficulties arise with palaeotechnic systems. Alloying metals, and perhaps some kinds of kiln-fired ceramics, are based on the ability to bring together disparate raw materials, often from distant separate sources. Such technologies appeared by the end of the Neolithic, perhaps 5000 years ago in the Old World, which is close enough to historic time as to engender no disagreement.

Prior to the appearance of alloying and kiln firing, the most direct technological evidence for EWM comes from the use of facilities (Oswalt 1976). These are gadgets and contraptions designed to function at a future time, occasionally in the absence of a human actor. Included are such palaeotechnic devices as traps, deadfalls, and weirs. They require contingency planning, conceiving action that is remote in time and space, and response inhibition, all hallmarks of EWM and its executive functions in general. The archaeological problem with such facilities is preservation; in prehistory such devices were often made of wood and fibre, which do not preserve well. Our best prehistoric examples are fish weirs and traps that came to be preserved in low-oxygen still water environments. These date back to the Archaic in North America and the Mesolithic in the Old World — perhaps 9000 years. In the deserts of the Levant, there are the remains of 'desert kites', which are stone structures used for driving gazelle. While these were likely to have been tended facilities, and as such less compelling than untended examples, some apparently date back to the Epipalaeolithic, which if accurate would extend evidence for facilities back to about 12,000 bp (Bar-Yosef 2002; Moore *et al.* 2000).

Facilities provide evidence for EWM back only to the end of the Pleistocene. A slightly less persuasive line of reasoning allows us to extend the evidence back another 20,000 years, perhaps even another 70,000 years. This line of argument is based on Peter Bleed's (1986) now classic concepts of reliable and maintainable weapons. Reliable weapons are designed to assure function, that is, to reduce as far as possible the chances for failure. As such they tend to be over-designed, complex in the sense of having several interrelated parts, hard to maintain, and often heavy. Indeed, reliable tools require 'down-time' for their construction and maintenance, and are most often intended to be deployed over short time spans of heavy use. The traps and weirs just discussed are good examples of reliable systems, but individual implements can also be reliable in this sense. A harpoon, for example, consists of several parts (detachable head, shaft, line, and float) that interact as a system. It is time-consuming to make, deploy, and maintain, but very effective if used properly. The guiding principle of reliable weapons is the investment of time and labour in advance of need in order to increase chances of success. Maintainable weapons, on the other hand, are simpler, lighter, more portable, and easily maintained on the spot. Maintainable weapons are less effective individually, but require less investment and downtime. Most, perhaps all, stone tools fall into this category.

Reliable weapons would appear to require the temporally-remote plans and contingency plans enabled by EWM and executive functions. Reliability implies an understanding of contingency; one over-designs a weapon in order that it is able to function in all contingencies. More telling, perhaps, is the necessity of down-time for tool construction and maintenance. This implies a use-life that is structured well in advance (see the following discussion of managed foraging), which is evidence of EWM.

What makes this line of reasoning less persuasive than that of facilities is not the concepts of reliability and maintainability, but our ability to recognize them in archaeological remains. The best examples are, as we have seen, facilities that are post-Pleistocene in date. Earlier examples of reliable technologies require judgments of time-investment and context of use, and are thus more open to challenge. Nevertheless, following Pike-Tay & Bricker (1993), we believe that one type of Palaeolithic artefact qualifies as being part of a reliable technology — the bone or antler point (a.k.a. sagai). For these artefacts, prehistoric artisans used stone tools to remove appropriately-sized blanks from antler or bone, and then further modified the blanks into specific shapes. Size and shape of these artefacts vary a great deal; some were simple lozenge shapes, others had rows of barbs. Most were intended to be projectile points hafted directly onto shafts, though some appear to have been harpoon heads. Broken points were often reworked into smaller functional units, attesting to their value in the eyes of the hunter, and the effort necessary to produce an entirely new artefact. The most spectacular examples, including harpoons, date from the European Late Upper Palaeolithic, from about 18,000 bp onward, but Early Upper Palaeolithic sites also have antler and bone points back as early as 30,000 bp. In Africa, bone points date back even earlier, perhaps as early as 90,000 at the Congolese site of Katanda (McBrearty & Brooks 2000). The European evidence is more compelling partly because of the contemporary evidence for managed foraging (see following) in which down-time would be a regular feature. The African evidence, while provocative, cannot yet be placed within a corroborating context of use. In sum, production and use of reliable weapons pushes evidence of EWM back to 30,000 years, and perhaps even 90,000 years.

Foraging systems

Managed foraging or manipulation of resources includes any subsistence system that relies on complex scheduling (e.g. Flannery 1968). (Note: It is not our intention to introduce a new term into descriptions of foraging systems. 'Managed' is a useful term for this analysis because it emphasizes actions governed by working memory and executive function in general. An extended version of this argument appears in Wynn & Coolidge 2003.) Here foragers must not only be flexible in terms of what to exploit on any particular day, but must weigh options with a mind toward future availability, and be prepared to change the system if necessary. The most obvious example is, of course, agriculture. Not only does agriculture require management of time, it requires considerable response inhibition when a portion of the harvest is retained for future planting, and response inhibition is one of the hallmarks of executive functions in general. Agricultural villages were well established in the Levant by 9000 years ago, with earlier examples such as Netiv Hagdud dating to perhaps a millennium earlier (Bar-Yosef & Belfer-Cohen 1989). But agriculture is not the only form of managed foraging. Most of the hunting and gathering systems that have been described as 'complex' (Price & Brown 1985) are managed systems. Classic ethnographic examples include foragers of the Northwest Coast of America, the Arctic, and Australia. Archaeological evidence for such systems extends back to the end of Pleistocene in the guise of Mesolithic, Epipalaeolithic, and Archaic adaptations. An especially good example is presented by the Epipalaeolithic site of Abu Hureyra in Syria, where a group of hunters and gatherers had established a sedentary community based on gathering a wide variety of local plants, and hunting that emphasized gazelle. With the increasing desiccation associated with the Younger Dryas climatic interval of 11,000 to 10,000 years ago, these people did not simply modify the focus of their gathering; they changed the very basis of the system itself by beginning to cultivate rye (Moore *et al.* 2000). The smoking gun here is not broad spectrum foraging, but the innovative response to changing conditions. These people must have been using the planning abilities enabled by EWM.

We believe that it is uncontroversial to characterize early Holocene foraging systems from around the world as managed. Earlier evidence is harder to document. The best example continues to be the western European reindeer hunters of the late Pleistocene. Straus (1996) describes the Magdalenian foraging system of SW France and northern Spain as '. . . a very specialized subsistence system (begun at least during the Last Glacial Maximum (*c.* 18,000 bp)) that included the interception and massive slaughter of migrating *Rangifer* herds; as well as more individualized killing on summer and winter pastures' (Straus 1996, 90). The system included sites located near funnelling points, where large numbers of individuals were killed, and smaller hunting camps. Though other resources were used, reindeer were the clear focus, and availability governed the mobility pattern of the hunters. Recall that these same Magdalenian hunters produced a reliable technology of barbed antler points and harpoons. Their yearly pattern of mobility would have included extensive down-time for maintenance and production of tools. We think that it is fair to describe this system as managed, and therefore evidence of EWM with its associated abilities of contingency planning and ability to project and plan future action. Contemporary groups in Africa and Asia are not as well known, though Later Stone Age groups in South Africa show some similarities (Deacon 2001), as do the late Pleistocene hunters who appeared on the plains of North America after 12,000 years ago.

Evidence from earlier than the Late Glacial Maximum is harder to interpret. We have already seen that Early Upper Palaeolithic groups produced bone and antler sagaies, though these were a bit simpler than those of the Magdalenian. Evidence from sites like the Abri Pataud (Pike-Tay & Bricker 1993) suggests that reindeer may often have been primary targets, but the evidence for massive slaughter and specialization is not as clear as it is for the Late Upper Palaeolithic, and more telling, a pattern that included smaller seasonal hunting camps is not evident. A slightly better argument for managed foraging in the Early Upper Palaeolithic relies on evidence for storage at Upper Palaeolithic sites on the Russian Plain. Here hunters killed animals in late summer/early fall and cached large quantities in pits for freezing and, we assume, future consumption (Soffer 1989). The earliest examples of such pits precede the Late Glacial Maximum, and increase in frequency during the subsequent Late Upper Palaeolithic where they were '. . . coterminous with the rise of complex base camps' (Soffer 1989, 727). Use of storage and delayed consumption is as compelling as the evidence for

Later Upper Palaeolithic reindeer hunting in SW France, and it extends evidence for managed foraging back another 5000 years or so to perhaps 23,000 bp. It does not, however, encompass the very earliest Upper Palaeolithic sites in Eurasia (*c.* 35–40,000 bp).

Middle Palaeolithic (MP) and Middle Stone Age (MSA) evidence is weaker still. There is evidence for specialized hunting at some MP sites. The best example is probably Saltzgitter-Lebenstedt in northern Germany, which dates to about 55,000 bp (Gaudzinski & Roebroeks 2000). Here Neanderthals utilized a 'small and steep valley' as an aid in killing reindeer. They apparently slaughtered many animals at a time, and preferentially focused on the prime adults during butchery (but see Munson & Marean 2003 for alternative view). A similar picture emerges from the Kenyan site of GvJm46, where faunal assemblages indicate '. . . a mass-kill site where the small extinct alcelaphine antelope was repeatedly killed in Late Pleistocene LSA and MSA times . . .' (Marean 1997, 217). Here, like at Saltzgitter-Lebenstedt, the hunters used a natural topographic feature to funnel animals into a killing zone, and, like their northern counterparts, reused the site on several occasions. A different kind of example corroborates this picture of effective hunting tactics. Sometime around 80,000 years ago a MSA hunter who used the site at Klasies River Mouth killed a *Pelorovis*, which was a giant Cape buffalo that weighed over 900 kg. The stone spear point that apparently helped kill it was found embedded in one of its vertebrae (Milo 1998; McBrearty & Brooks 2000). What makes this case provocative is the sheer size and ferocity of the beast (if the modern smaller Cape buffalo is any guide). Whoever killed it must have had an effective tactic (as well as considerable audacity).

Gaudzinski & Roebroeks (2000) and McBrearty & Brooks (2000) believe such evidence compares well with the evidence from the European Later Upper Palaeolithic, and that it represents advanced abilities. We pose a slightly different question. Did this kind of hunting require a managed approach to foraging that would implicate EWM? Reluctantly, we think not. Specialized hunting and reuse of sites implicate tactical hunting, to use Marean's term, but effective tactics can exist without the kinds of contingency planning and flexible scheduling that are true of managed systems. Indeed, the reuse of sites over centuries or millennia suggests (but does not require) a system in which change was not a component. We think that sites like Saltzgitter-Lebenstedt and GvJm46 testify to very effective hunting tactics, but these were systems that did not require the services of modern EWM. What distinguishes the European late Upper Palaeolithic system is not specialization, *per se*, but the evidence for flexibility, in the guise of the variety of Later Upper Palaeolithic reindeer hunting sites, and storage. This may simply be a reflection of their more recent date and concomitant better preservation, but we cannot ignore the possibility that it is a real trend over time.

Information processing

An algorithm is a device for solving problems. It can be a set of rules for manipulating information (e.g. arithmetic) or an actual artefact that can be used to calculate solutions (e.g. an abacus). True algorithms are learned every generation and, once learned, become part of the corpus of cultural knowledge carried in long-term memory. But they are manipulated by working memory. Arithmetic is a well-studied example. 'The longer the individual's working memory capacity and the faster the individual could execute the retrieval and carrying process, the better his or her performance on arithmetical word problems' (Geary 1999, 268). Studies of pre-schoolers reveal that their difficulties in basic arithmetic calculation (presented in non-verbal problems) can be attributed to the number of elements that must be held in working memory, which is partly a function of brain maturity (Klein & Bisanz 2000). What is true of arithmetic is true of other algorithms; they are deployed in working memory to help solve specific problems. But algorithms also ease the load on working memory, thereby enhancing the ability to solve problems. When confronted with a problem one can first choose an appropriate algorithm and hold it in working memory as a simple token (e.g. 'associative rule'), rather than reason through the relationships anew. This frees up working-memory capacity for the access and manipulation of specific content. Better still are algorithms that take up no working memory at all; that are in fact, physically separate from the brain itself. These are computational artefacts of all sorts — calendars, oracle bones, and graphing calculators. It is clear that algorithms enhance working memory; what is not as obvious is that they rely on EWM. Even as a simple token, the algorithm takes up working-memory capacity — either held in phonological storage or manipulated by the central executive. We hypothesize that EWM enables the expanded attention window necessary to access and process algorithms and content at the same time.

As such, evidence of algorithms is compelling evidence for EWM. And, luckily, some computational devices are preserved in the archaeological record. Marshack (e.g. 1985; 2002) called attention to these devices in his controversial claims for lunar calendars in the European Palaeolithic and even pointed out the importance of limited frontal-lobe abilities. Recently, d'Errico (2001; d'Errico *et al.* 2001) has made a study of these objects, and comes to a different (if less romantic) interpretation. The relevant objects consist of pieces of bone with patterns of marks (dots, lines, and dashes). For several of these it is possible to document the successive use of different engraving tools, which suggests that engraving took place at different times. While the specific use of these objects still eludes us, it does appear that the makers were keeping track of something (days, seasons, game, menstrual cycles, etc.). Any such device is a cultural algorithm.

Once again, chronology and preservation complicate the archaeological picture. The most famous such artefacts date to the very end of the Palaeolithic — the Taï plaque dates to the final Magdalenian, the Tossal de la Roca plaque to the Iberian early Epipalaeolithic, and the more controversial La Marche plaque to the Middle Magdalenian. Patterns of marks appear on objects from the European Early Upper Palaeolithic (e.g. Aurignacian, *c.* 30,000: Marshack 1985), but they are less convincingly sequential in nature. Similarly, there is now quite convincing evidence of an engraved bone from the South African Middle Stone Age site of Blombos Cave (d'Errico *et al*. 2001), which dates back 80,000 years or more, making it the oldest widely-acknowledged engraved object ever found. Here again, however, there is no evidence for sequential marking, and while it may have significance for other behaviours, the object is not clearly an algorithmic device.

Narrative is another kind of information-processing, but here the emphasis is on storage and retrieval, and the implications for working memory are therefore less clear. As noted earlier, Sugiyama (2001) has argued that narrative evolved as a vehicle for relaying and sharing information, and that there has been selection for a specific organizational structure, or in the terms of evolutionary psychology, a dedicated cognitive module. Moreover, she dates the advent of this adaptation to the appearance of modern humans with modern language. We agree with her emphasis and dating, but suggest that, rather than representing a specific cognitive module, narrative is more simply understood as being structured by EWM. Since working memory accesses episodic memory, and can associate and coordinate its outputs, it is almost certainly the key to the construction of narrative. Interestingly, despite narrative's expression in words, it is not generated from semantic memory, except in the special instances when lists become part of the story (e.g. the 'begats'). Stories are memorable because they access the kinds of information stored in episodic memory and coordinated in working memory. In other words, narrative is a good indicator of EWM.

Unfortunately narrative does not leave direct archaeological traces until the appearance of writing. While *Gilgamesh* is clearly narrative, and its content suggests a narrative tradition of considerable antiquity, it is still very recent in an evolutionary sense. Archaeological evidence for earlier use of narrative is always indirect, and based on chains of inference. For example, the 'bird-headed' man at Lascaux is part of an enigmatic tableau of paintings that *could* represent an episode in a narrative. Many similar examples can be cited from European Upper Palaeolithic and South African Later Stone Age art. To modern eyes it seems as if narrative lurks behind some or all of these paintings, and narrative requires EWM. The difficulty, of course, is that there are alternative interpretations, and authorities are far from unanimous in their accounts of the genesis of these paintings. They are provocative, but in themselves not convincing.

In sum, it is possible to document evidence of algorithmic thinking back to the end of the Palaeolithic, perhaps 14,000 years ago. Earlier evidence for cultural information-processing systems like narrative is provocative, but does not antedate the European Upper Palaeolithic or the African Later Stone Age.

A provocative isolated case

People colonized Australia at least 60,000 to 70,000 years ago, an event that required them to sail over the horizon in boats (e.g. Coupé & Hombert 2002; Davidson & Noble 1992). Indeed, it is very tempting to cite this achievement as the earliest evidence for EWM, much as Klein (2000), and Davidson and Noble and others have used it as evidence for symbolic language and modern behaviour in general. It probably required projecting future action, group contingency planning, and the production of elaborate, multi-step technologies (boats), all activities that are enabled by EWM.

Discussion and summary

The archaeological evidence suggests a recent acquisition of enhanced working memory. Indeed, if we rely on a strict standard of evidence, then we can trace EWM back only about 14,000 years. By a strict standard we mean evidence for activities that clearly required EWM, and whose archaeological signature is beyond question. The managed foraging systems of the Epipalaeolithic, Mesolithic, and Archaic all qualify, a conclusion nicely corroborated by the evidence for use of facilities. Use of sequential notational devices like the Taï plaque extends evidence back to the very late Palaeolithic, but no further. Less strict standards of evidence, in which either the necessity for EWM or the archaeological evidence are open to question, allows us to push the record back to 30,000 years with little hesitation (engraved plaques, reliable weapons, storage), and to 80,000 years with considerable hesitation (specialized hunting, bone tools). There are two ways to interpret this rapid fade in the archaeological signature of working memory. First, what we are seeing is merely the expected degradation of evidence that reflects preservation and the probability of discovery (as discussed by Bednarik 1994 for the evidence of art). Pursuing this argument, one could suggest that EWM was in place at least 80,000 years ago, but that the evidence only emerges from sites occupied close enough to the present to be well-preserved and commonly found. Second, we can take the record as a more or less accurate reflection of the evolutionary sequence, in which case we must be able to account for the rapid fade in terms of evolutionary processes and events. And here again we have two options, though they are not mutually exclusive: first, the record is simply that of the ascendancy of anatomically and behaviourally modern humans and, second, that EWM altered the nature of culture itself and, in a sense, enabled progressive change.

The first option is the more conservative and Darwinian, and fits nicely with interpretations of recent human evolution that grant behaviourally modern humans some evolutionary advantage over their more archaic contemporaries. Most commonly the advantage has been attributed to language (e.g. Mellars 1989; 2000), though Klein (2000) hints at something else. EWM as described here meets all criteria for Klein's simple mutation (except that we posit either a single but profound allele or an evolutionary sequence of a few alleles in a relatively short period of time). Of special significance is the 'size' of the effect — a few alleles enhancing the operating capacity of working memory. Initially it would have appeared in low frequencies in anatomically modern populations, presumably in Africa. As modern populations spread out of Africa, the allele frequency within these groups increased via classic Darwinian, or even non-Darwinian, mechanisms, so that more individuals expressed the trait. In this scenario, the rapid fade in the record reflects both the expansion of modern humans and the increase in the frequency of the alleles (and recall that non-EWM alleles still occur in significant frequencies in all modern populations). EWM may not have conferred a dramatic competitive advantage over more archaic humans, at least not at first. But as more and more modern humans expressed the trait, the advantages of group contingency planning would eventually lead to adaptive solutions against which archaic humans could not compete.

This first scenario largely ignores culture change, and focuses on relatively simple Darwinian mechanisms. The alternative focuses not on population genetics, but on the possible effect of EWM on culture itself. We believe that the enlarged attention window created by EWM may be the cognitive development that enabled the appearance of true innovation in culture change. By true innovation we mean the ability to form intentionally a new solution to an immediate problem, i.e. fluid intelligence. EWM enables innovation by making analogy and thought experiment possible. In analogical thinking one applies patterns from one domain to the content of another domain, thereby generating potential new solutions to old problems. Thought experiments work by projecting action into the future, and this ability has even been proposed as one of the keys to modern thinking, as we noted earlier (e.g. Shepard 1997). Both analogy and thought experiment require holding a variety of information in mind at the same time, and this attention window is *the* domain of working memory.

One of the truisms of Palaeolithic archaeology is that immense spans of time passed during which there was no perceivable culture change. For most of the Palaeolithic, change occurred on an evolutionary scale, but not on the historic scale that we find in the modern world. It was not until the very late Palaeolithic that the pace of culture change itself shifted gear and entered the mode of accelerating change that characterizes the modern world. We see evidence for this in bone and antler tools and in stone tools, which for the first time, present patterns of stylistic change (Bar-Yosef 2002). We are not arguing that EWM caused this; only that innovation depends on the enlarged attention window produced by EWM. Arguably, innovation is also a regular feature of managed foraging systems and information-processing systems (e.g. a calendar is an algorithm derived from analogy between a tally stick and the passage of days, or moons, or seasons). Moreover, it underpins the well-known 'ratchet effect' of technological change (Basalla 1988), in which modifications accumulate progressively over generations. Tomasello *et al.* (1993) have argued that the ratchet effect depends on the intersubjectivity of collaborative learning; we suggest that EWM is also a necessary component. In addition, EWM would have had a significant impact on social complexity. If one can hold 'more things in mind', one can imagine and manipulate more complex social scenarios, increase level of intentionality ('I know that you know that I know . . .'), make more elaborate justifications and rationalizations, and generally play the social game more effectively (e.g. theory of mind). Much of this would be invisible archaeologically. But archaeologists know that technology plays an active role in social life. We suggest that this active social role for tools may have been enabled by EWM, and the tangible result was that rapid change in styles that characterizes modern material culture. If, as we contend, EWM enabled progressive change, then we would expect the evolutionary record to be one of slow, accelerating change, with the initial evidence for this kind of cultural change post-dating, perhaps by millennia, the first appearance of the alleles.

The preceding two options are not mutually exclusive; it is possible, even probable, that the evolutionary fate of EWM alleles was intimately tied to their effects on social complexity, cultural transmission and innovation. Gradual increase in the frequency of the alleles, along with the ratchet effect of progressive cultural change, should yield an evolutionary record very like the one we can document for the last 100,000 years.

Modern thinking

Certainly, it must be allowed that Neanderthals and other archaic humans had some conscious propositional thinking. The decisions involved in Oldowan, Acheulean, and Middle Stone Age tool-making show an evolution in thinking, including the coordination of spatial- and shape-recognition systems and increase in the capacity of expert memory systems (Wynn 2002; Wynn & Coolidge 2004). These developments would certainly have required an enhanced visuospatial sketchpad, but they need not have been rooted in language. Decisions made upon information held in the visuospatial sketchpad could be made by the central executive without necessarily engaging the phonological store. It is also possible, as suggested by Rossano (2003), that expertise in tool making may have served as a kind of prototypical consciousness. As Carruthers (2002) notes, however, many learned habits and linguistically-acquired patterns of thinking, such as long division (an algorithm!), could only be conducted consciously through inner speech and language. The result is a dual process of human reasoning (as recently advanced by Stanovich 1999). There is a powerful, quick, implicit, affectively-based decision-making system, and a slower, serial, explicit, and language-bound reasoning system. Carruthers reasons that the latter system is conscious (or *is* the nature of consciousness), and largely under personal control through inner speech. We suggest that it may have been enhanced phonological storage that ultimately linked these two reasoning systems. The enhancement of phonological memory capacity may have also been influenced by increased rates of rehearsal or by other factors such as an increased speed of memory-scanning during retrieval or some other feature of the central executive. We have also proposed that enhanced phonological storage may have freed language from the laconic and its confinement to present tense and simple imperatives to rapidly-spoken speech and the use of future tense — the linking of past, present, and future, and the use of the subjunctive (e.g. Klein & Edgar's 'what-if' statements). Of course, there were dramatic and latent costs involved in the evolution of modern thinking. Although real enemies' actions might be anticipated, imaginary enemies could be envisioned, and other intangible terrors could be given life. Great anxieties could arise with novel vistas (e.g. the meaning of life, thoughts of death, life after death, etc.). Nonetheless, EWM may have allowed the evolution from stone tools to moonwalks in just 100 millennia.

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