

The role of working memory in the evolution of managed foraging

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Abstract

This article proposes that a relatively simple evolutionary development in human cognition enabled the development of managed foraging systems and, ultimately, agriculture. This development, an increase in the capacity of working memory, resulted in an enhancement of such specific cognitive abilities as response inhibition, response preparation, resistance to interference, and the ability to integrate action across space and time. All are required for modern managed foraging systems, including hunting and gathering and agriculture. Archaeological evidence provides strong evidence for managed foraging by the middle of the European Upper Palaeolithic and South African Later Stone Age, and independent evidence for enhanced working memory capacity slightly earlier. This fits the hypothesis that enhanced working memory capacity was a relatively recent development in human evolution, and one that enabled not just managed foraging, but perhaps modern culture itself.

1 Introduction

In 1997 Andrew Sherratt reintroduced the variable of human cognitive ability into discussions of the origins of agriculture:

This description emphasizes the stored-up potential for change which was released by the onset of interglacial conditions. A propensity to interfere with the environment in unexpected ways seems to have been an inherent characteristic of modern humans....behaviourally modern people like to mess around with plants... (Sherratt 1997:279).

Sherratt here addresses a perennial problem in theories of agricultural origins: such proposed triggers as climate change, or new plant associations, had all occurred many times during the course of the Pleistocene. Even local population stress was unlikely to have been unique to the late or early post Pleistocene. So why hadn't agriculture appeared earlier? Why didn't early *Homo sapiens* take up agricul-

ture at the end of OIS 6, or *Homo erectus* earlier still? Sherratt merely articulates a generally held suspicion that abilities or behaviours carried by modern humans were somehow prerequisite to the development of farming; hence his reference to 'propensity to interfere with the environment' and liking to 'mess around with plants.' In a footnote he is even more explicit about a cognitive component: 'Hence the popularity of gardening as a hobby. This is in part a displacement of social categories onto plants, a classic example of the cognitive procedures and analogical reasoning of *Homo sapiens sapiens*' (ibid:279).

We agree with Sherratt, and suggest further that a relatively simple neurological development enabled not just agriculture, but all of the complex managed foraging systems that appeared world wide toward the end of the Pleistocene and early Holocene. All of these foraging systems depend on frontal-lobe linked abilities known collectively as executive functions and which, we contend, reached modern capacity through an enhancement in working memory caused by a relatively simple mutation. Here we also agree

with Klein (2000) that this evolutionary development may have occurred after the appearance of anatomically modern humans.

2 Executive functions and working memory

Generally considered, executive functions are a group of cognitive abilities used to organise and execute flexible, contingent, plans of action. They incorporate such specific abilities as response inhibition (suppressing a natural response like fight or flight), response preparation (projecting future action), resistance to interference (ability to hold attention in spite of distraction), and the ability to integrate action across space and time (coordinate action with distant, unseen actors) (Pennington & Ozonoff 1996; Coolidge & Wynn 2001). Barkley (2001) takes an evolutionary perspective to executive functions, and emphasises the central role of self-regulation: 'The EF's [executive functions] are composed of the major classes of behavior toward oneself used in self-regulation. An executive act is any act toward one's own behavior so as to change the future outcomes for that individual' (ibid: 5). Much of the early research on executive functions consisted of neuropsychological studies of individuals with brain damage to the frontal lobes, and indeed executive functions were often simply equated with frontal lobe function. More recently, neuroimaging techniques like fMRI (functional magnetic resonance imaging) and PET scans (positron emission tomography) have enhanced resolution of frontal lobe function. Gazzaniga, Ivy and Mangun (2002) now argue that EFs do not reside in a single frontal lobe structure, but result from the interplay of diverse cortical and sub-cortical neural systems, most of which lie in the frontal lobes. In addition, one of the leading hypotheses concerning ADHD (attention deficit, hyperactivity disorder) is that this relatively common disorder stems from an executive function deficit. Studies of inheritance of ADHD suggest that core EFs have a relatively simple additive genetic inheritance pattern (as few as four pairs of alleles) and are highly heritable (approximately 77%) (Coolidge et al 2000).

Over the past fifteen years evidence has accumulated that executive functions are the attendant features of working memory. As conceived by Baddeley (1986, 2000), working memory is a form of temporary neural storage that receives input from other neural

systems and holds them in active attention, thus allowing further processing. It is the system that 'holds things in mind,' enabling such executive functions as response inhibition and preparation, resistance to interference, and integration across space and time. Based on experimental results, Baddeley developed a model for working memory that included an attentional panmodal control or central executive, and two slave sub-systems, an articulatory phonological store that maintains speech-based information, and a visuospatial store, also known as the visuospatial sketch-pad, that holds and maintains visual (eg, images) and spatial (eg, relative location) information. Both sub-systems can maintain information in active attention for only a few seconds, after which there is rapid fade, but both also include means of refreshing information through mental rehearsal (eg, the sub-vocal rehearsal one uses when trying to remember lists). While a few seconds may not appear to be much time, it is within this attention window that the mind does its active business, including retrieving information from long-term memory and comparing it to other memory traces and to current perceptions. It is within this window, for example, that speakers construct sentences and, on the receiving end, recover meaning from words and syntax. Kane and Engle (2002) have recently confirmed the link between working memory capacity, as measured by multiple cognitive tasks (it cannot be measured by only one), and performance on tests of general intelligence. Moreover, their review of brain imagery research indicates that the neural architecture activated during executive attention tasks (their term for the central executive of working memory) is located in the dorso-lateral prefrontal cortex.

It appears, then, that 'working memory' is the generic term for Baddeley's larger cognitive model, while the terms 'central executive' (Baddeley) and 'executive attention' (Kane & Engle) are essentially synonymous and refer to the central control function. The term 'executive functions', then, refers to the behavioural features or abilities generated by the central executive or executive attention. These terms collectively refer to a complex mental ability that can be linked reliably to a particular area of neural architecture. This highly interrelated system to 'hold things in mind' can also be referred to as 'working memory capacity,' and it appears to be a key component of general intelligence (indeed, Kyllonen [1996] equates

the two). Working memory capacity also has been shown to be strongly correlated to fluid intelligence, that is, the ability to solve novel problems (Kane & Engle 2002). Brain imaging also indicates that the same neural structures are highly involved in formal deductive logic and syllogistic reasoning (Kane & Engle 2002). Any enhancement of working memory capacity should have profound consequences for the mind's ability to manipulate information. Also, it is important to note that the word 'capacity' is not used here in the sense of storage or of size, but of an ability to maintain pertinent information in an active state and relevant to goal attainment, especially in the presence of interference.

We suggest that developments in executive functions, in particular an enhancement of the capacity of working memory, were key to the evolution of modern cognition. Three features of enhanced working memory (EWM) capacity lead us to grant it priority over other proposed keys to modernity like symbolism. First, it is the appropriate magnitude. Compared with those who possess the trait, individuals lacking EWM are only slightly impaired in ability. They can anticipate future states, make the arbitrary connections necessary for symbol use, and employ complex action sequences that have been committed to long-term memory. Indeed, the vast majority of even modern activity can be performed without EWM (driving to work is an overused example). But to suggest that the evolutionary enhancement of working memory was a small change is not to suggest that it was insignificant. The expanded attention window of EWM allowed more sophisticated contingency planning and innovation (through analogy and thought experiment), activities that are crucial to modern culture. Second, EWM is fairly simply inherited, the best current model suggesting the additive effect of only four gene loci. EWM was not the result of a massive reorganisation of the brain, but instead was a modest development that had profound consequences. As such, it is an almost perfect candidate for Klein's proposed mutation that led to behavioural modernity. Third, EWM has provocative links to that other posited key to modernity, language. This position, similar to that of Ambrose (2001), requires some explication, given the central role assigned it by many students of human evolution. We suggest that the expanded attention of EWM was the cognitive development that enabled modern grammatical complexity, including a flowering

of tenses and an enhanced ability to generate and understand long utterances. This position acknowledges the likelihood that symbolism and simple grammar were components of archaic human communication. To us the reverse scenario in which the evolution of an 'inner speech' capacity enabled complex reasoning (see Carruthers *in press*), seems less likely, if for no other reason than its neural basis is far more diffuse, and less clearly understood, than that for working memory. In addition, the expanded attention window and ability to 'hold things in mind' probably enabled the creation of complex narrative structures, which have a clear role in communication of information (Sugiyama 2001).

3 Managed foraging

Enhanced working memory capacity yields important consequences for most domains of human action. Barkley (2001), for example, argued that the clearest consequences must have been in the domain of social interaction, where contingency planning and ability to conceive and view oneself in alternative future scenarios would have yielded a clear advantage. Ironically perhaps for archaeologists, EWM provides relatively few clear advantages in technical activity. Most modern technical activity is still based on procedural memories laboriously learned through apprenticeship and encoded into long-term memory. EWM does underpin innovation, but this remains a tiny piece of technical repertoires. Like technology, most subsistence activity is learned by observation and apprenticeship, and indeed is largely a non-verbal undertaking, especially in palaeotechnic systems (Gardner 2002). Like technical activity, routine subsistence activity rarely engages the most powerful resources of EWM. But rarely is not never, and EWM does play a crucial role in the general category of subsistence we term managed foraging.

Managed foraging systems are ones in which people consciously manipulate their activity, and occasionally even plants, animals, and landscapes, in order to maximise their gain or to adjust to new conditions. Managed systems are roughly synonymous with 'complex foraging' (Price & Brown 1985), but we choose to risk confusion by emphasising management rather than complexity. Management requires contingency planning, response preparation and inhibition, and integration across time and space, all features of EWM.

Modern subsistence systems are managed. Agriculture, in all its guises, presents the most obvious example. Even palaeotechnic agricultural systems rely heavily on the full array of executive functions. Response inhibition is necessary if a portion of a current harvest is retained for future planting (don't eat the seed corn), or if individual animals are spared because of future benefit (don't eat your oxen). Response preparation, based on projected future action and contingent response, governs the lives of agriculturalists – fallow systems, crop rotation, staggered planting, etc, are all examples of contingent planning. Farmers and pastoralists must anticipate problems and prepare responses. True, most agriculturalists develop complex ritual (or scientific) devices to help them do this, but the fundamental pattern of thought is based on executive functions. Perhaps more telling is the necessity for innovation. Ritual knowledge, entered into long term memory, can govern most year-to-year agricultural activity. In times of stress, when the system fails, agriculturalists must respond in novel ways, and such responses depend on the thought experiments, analogies, and new combinations enabled by enhanced working memory.

Agriculturalists are not alone in deploying these cognitive resources; indeed, they are only one example of a managed system. Most, if not all, foraging systems documented in the ethnographic record are also managed systems to one degree or another (Williams & Hunn 1982). Perhaps the clearest examples are fishing based economies like those of the Northwest Pacific coast of America. Here seasonal runs of salmon and candle fish present a resource opportunity that, if managed effectively, can provision a group for the entire year. The general management solution developed by Native Americans included both technological and social elements. The key technologies were preservation and storage, and the use of facilities (Oswalt 1976). Storage, especially when combined with preservation, is clearly an executive function activity. One must suppress the natural response to consume a food (or use it to gain immediate social advantage), and then, often, modify the food into a form that is less immediately desirable, all with the intent to consume or use it at a much later date. Response inhibition, response preparation, and integration of action across time are all necessary. These fishing peoples not only stored, they planned their entire year around fishing for anadromous fish,

an annual system fully as complex as those deployed in agriculture. Facilities are immobile technologies like traps, deadfalls, and weirs. They are more labour intensive to produce and maintain than simple implements like stone tipped spears, but are more reliable (Bleed 1986). Untended facilities are especially good markers for EWM because they capture remotely, and some of the facilities built by Northwest (NW) Coast peoples clearly qualify (fish traps, deadfalls) (Oswalt 1976). In addition to technologies, NW Coast social systems incorporate social elements such as ownership and feasting that serve to manage and distribute the abundant resource (Richardson 1982; Daly 1999). The planning of feasting, and the social machinations of conspicuous consumption, themselves rely on EWM; Machiavellian tactics rely on response inhibition, preparation, and contingency (Barkley 2001).

Tropical environments have a much greater variety of animal and plant resources, and often a much higher biomass than temperate and cold environments. Moreover, the resources are spread more evenly throughout the year. As a consequence, high latitude and temperate foragers are more likely to rely more heavily on meat than low latitude foragers (Binford 2001), and are more likely to employ specialised techniques for acquiring large numbers of animals at one time (Marean 1997). Most if not all of the historically known groups of bison hunters on the North American plains, for example, planned their years around communal hunts and the stored animal products that were a result (Bamforth 1988). However, specialisation or mass kills *per se* do not require management; they only require an effective tactic (usually communal) for hunting each species. That all modern specialised hunters also use managed strategies does not require that this always was so.

Tropical hunters and gatherers also employ management strategies, even though they appear not to practise the specialised management techniques of high latitude hunting and fishing economies. A cursory survey of ethnographically documented hunters and gatherers reveals that management is widespread, if not ubiquitous. The Penan of southeast Asia avoid harvesting sago palms in depleted areas, allowing the trees to recover for several years (Brosius 1999). Aboriginal Australians in northern and Western Australia regularly and systematically

employed fire to manage local plant communities. Burning encouraged rapid 'greening up' after a subsequent rain, and greening up attracted herbivores. Moreover, regular burning of small parcels forestalls catastrophic large burns. Aboriginal groups systematically staggered burning of small parcels in order to manage the availability of game (Lewis 1982). We believe this controlled use of fire to manage and alter natural ecological timing is clearly based on EWM. All of the specific cognitive components are implicated: response inhibition in setting large scale fires, response preparation in selection of patches and timing of burns, and integration across space and time in the overall timing of burns and projection of consequences.

These examples, from very different environments and very different hunting and gathering strategies should be sufficient to illustrate our point. All modern foraging systems, not just agriculture, are managed systems in which people rely on contingent plans of action, and actively manipulate the resources they use. These plans of action are generated by enhanced working memory.

4 Prehistoric evidence

It is probably not controversial to argue that all modern subsistence systems are managed by and dependent upon modern cognition. Specifying EWM as the key component of cognition that enabled management is more controversial, but clearly defensible. However, in order to support the hypothesis that EWM was the key evolutionary development that led to managed foraging systems and, ultimately, agriculture, it is necessary that the evolutionary timing be right. If, for example, archaeological evidence for EWM or managed foraging could be traced back to the early Pleistocene, then they could not have played the roles we ascribe to them. In order to support Sherratt's hypothesis it is necessary that managed foraging systems antedate the end of the Pleistocene, so that this climatic trigger could push some groups into food production. It also important that independent evidence for EWM antedate evidence for managed foraging. We believe that the archaeological evidence supports this scenario.

4.1 Antiquity of managed foraging

Compelling evidenced for managed foraging dates back at least 12,000 years, and strong evidence

pushes the date back to the Last Glacial Maximum. The compelling evidence consists of Epipalaeolithic sites from the Levant. Archaic systems in North America and Mesolithic systems in Europe are also compelling examples of managed foraging, they just do not have quite the antiquity of the Near Eastern example.

The single best example comes from the Syrian site of Abu Hureyra (Moore et al 2000). Here, about 12,000 years ago, people established a small sedentary community on a terrace above the Euphrates River. Flotation results indicate that they exploited a wide variety of seed bearing plants from the Euphrates river bottom and from local woodland-steppe and nearby park-woodland habitats, including wild cereals and other grasses. They also hunted, with an emphasis on gazelle. Theirs was a classic example of 'broad spectrum' foraging combined with limited residential mobility. In this they were similar to later Mesolithic and Archaic peoples in Europe and America. But a broad spectrum of resources and sedentary settlement do not in themselves logically require management (though the correlation would appear to be very high) or EWM. The compelling case for management comes from Abu Hureyra's response to change. By 10,400 years ago, and perhaps half a millennium earlier, these people were using domesticated rye, and domestication implies manipulation and management (for example, moving rye outside of its natural stands, or encouraging its growth by elimination of competitors). Instead of simply shifting the emphasis of their foraging to new or little used resources, they changed the very nature of their relationship with particular plants to include direct manipulation. That this may have been a response to increasing dessication of the Younger Dryas of course supports Sherratt's specific hypothesis for the origin of agriculture, but for the present it is important for its documentation of managed foraging prior to the establishment of the first agricultural villages (which, interestingly, did not rely on rye). Similar sedentary sites occur elsewhere in the Levant at about the same time: Ain Mallaha with its stone house foundations, storage pits, and evidence for cereal harvest, and Mureybit with evidence for storing wild einkorn (Bar-Yosef & Belfer-Cohen 1989; Smith 1998). Contemporary hunting camps also show evidence that Epipalaeolithic hunters preferentially selected adult male gazelle, a form of selective hunt-

ing that also implies management (Moore et al 2000). Indeed, the late Epipalaeolithic people of the Levant present a picture of a very flexible kind of managed foraging that could be easily and quickly tailored to local circumstances and changes in local conditions. Some of these groups eventually turned to direct manipulation of resources, which resulted in domestication and, eventually for some, farming.

Earlier use of managed foraging is harder to document. The best example continues to be the western European reindeer hunters of the late Pleistocene. Straus (1996) described the Magdalenian foraging system of southwest France and northern Spain as '...a very specialized subsistence system (begun during the Last Glacial Maximum) that included the interception and massive slaughter of migrating Rangifer herds; as well as more individualised killing on summer and winter pastures' (1996:90). This system included sites located near funnelling points, where large numbers of individuals were killed. Some kind of preservation seems likely to have been practised, though there is no direct evidence for it. The system also included smaller hunting camps, and it is clear that the hunting practices varied, perhaps as Straus implies, on a seasonal basis. Though other resources were used, reindeer were the clear focus, and availability governed the mobility patterns of the hunters. These same Magdalenian hunters produced a reliable technology of barbed antler points and harpoons; their yearly pattern of mobility must have included extensive down time for maintenance and production of tools. What is provocative about these reindeer hunters is not specialisation *per se*, but the indications that year-round procurement of reindeer was the centre piece of the subsistence system. This required not just a variety of tactics, to be employed as necessary or appropriate, but a strategic plan of action for perhaps an entire year. Magdalenian cave art, a perennial source of speculation about the late Palaeolithic life-world, indicates at a minimum that these people had significant down time in their yearly cycle, and the likely use of calendar-like devices (see below) attests to a temporally ordered approach to life, a point made long ago by Marshack (eg, 1972). This variety of evidence leads us to conclude that the Late Upper Palaeolithic (LUP) of western Europe had elements of a managed foraging system. The evidence is not, however, as convincing as that for the Epipalaeolithic, primarily

because there is no evidence for innovative solutions, the kind that would require the analogical reasoning and thought experiments enabled by EWM. Contemporary groups in Africa and Asia are not as well known, though Later Stone Age (LSA) groups in South Africa show some similarities (Deacon & Deacon 1999), as do the late Pleistocene hunters who appeared on the plains of North America after 12,000 years ago.

Two examples allow us to push evidence for managed foraging back to perhaps 23,000 years ago. Evidence from Early Upper Palaeolithic (EUP) sites like the Abri Pataud suggest that reindeer may often have been primary targets (Pike-Tay & Bricker 1993). However, the evidence for massive slaughter and specialisation is not as clear as it is for the LUP; indeed Grayson and Delpech (2002) have argued that the degree of specialisation practised by EUP hunters in southwestern France was very little different from that of the preceding Middle Palaeolithic. Just as telling, a varying pattern that included smaller seasonal hunting camps is not evident. A slightly better argument for managed foraging in the EUP relies on evidence for storage at sites on the Russian Plain. Here hunters killed animals in late summer/early fall and cached large quantities in pits for freezing and, it can be assumed, future consumption (Soffer 1989). The pits are 1-1.5 m in diameter and about one metre deep, and hunters stacked large 'packages' of meat (eg, not filleted) in bundles. The earliest examples of such pits precede the Last Glacial Maximum, and examples increase in frequency during the subsequent LUP 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 LUP reindeer hunting in southwest France, and it extends evidence for managed foraging back another 5,000 years.

Roughly contemporary sites in South Africa provide evidence of a different sort. For example, Klein and Cruz-Uribe observe that 'The overwhelming majority of seal humeri from LSA sites fall comfortably within the size range of known 9-11 month olds (Klein 1994), suggesting that LSA people timed their coastal visits to fall within the (August-October) peak in juvenile seal availability' (Klein & Cruz-Uribe 1996: 327). Such timing is characteristic of managed systems. The site of Strathalan yields evidence for the use of corms from *Watsonia* (a plant in the iris family)

(Deacon 1993; Deacon & Deacon 1999). Corms are carbohydrate rich underground stems of geophyte plants. After fires, nutrients from the ash stimulate a flowering of the plant and a division of the corm itself. 'To be productive as food sources, geophytes need to be fire managed. Farming with fire can be inferred for both the Middle and Later Stone Ages, and it is practiced by contemporary hunter-gatherers' (Deacon & Deacon 1999:98). We find Deacon's argument for the LSA evidence to be persuasive. More recent sites than Strathalan, such as Melkhoutboom, provide abundant evidence for scheduled use of plants, including corms, and the 23,000 date for the MSA at Strathalan is a reasonable extension of this set of activities. Deacon's argument for the Middle Stone Age at Klasies River Mouth is far less persuasive (see below).

In sum, there is reason for extending the record for managed foraging back to 23,000 years ago. We admit to being very conservative here. We could, for example, simply conclude that all EUP and LSA foraging systems were managed because we do have possible examples at 23,000. But this would assume what must be demonstrated. We cannot conclude that EWM or managed foraging was in place simply because a particular culture-stratigraphic unit is in evidence. Earlier EUP and LSA sites do not themselves present good evidence for managed foraging.

Despite some analyses that suggested Middle Palaeolithic (MP)/Middle Stone Age (MSA) foraging was dependent to a significant degree on scavenging (Binford 1981, 1984, 1985), current analyses of zooarchaeological evidence indicate that hunting was an important part of the repertoire, and probably a dominant activity in the high latitudes occupied by Neanderthals (Marean & Assefa 1999). There remains disagreement about the nature and range of variability of MP/MSA hunting. Analyses of use wear on some Levallois points, for example, indicate that many were hafted onto spears and used for thrusting (Shea 1999, 1993, 1998); moreover, analysis of Neanderthal injuries indicates a high frequency of the kind of trauma that would occur with close-in killing of large mammals (Berger & Trinkaus 1995). Several MP sites in Europe have yielded evidence that MP hunters may often have focused on single species. At the site of Salzgitter-Lebenstedt in northern Germany, which dates to about 55,000 BP (Gaudzinski & Roebroeks 2000), Neanderthals utilised 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, an interpretation recently challenged by Munson and Marean (Munson & Marean 2003). Open-air MP sites in southern France provide evidence for the almost exclusive processing of single species of bovid (aurochs at La Borde, bison at Coudoulous and Mauran, and indeterminate bovid at Le Roc [Mellars 1996]). Massive accumulations of horse bones below a steep cliff at La Quina even suggest that the animals had been driven (Mellars 1996). Focus on or preference for single species does not require management, however, even in cases where mass kills may have occurred. It attests to effective tactics, but does not require the weighted scheduling of a managed strategy.

Given the high latitude habitats used by the European Neanderthals it is not surprising to see evidence for hunting, and even tactics for mass killing; as with modern hunter/gatherers, meat must have assumed increasingly greater importance the farther the hunters moved from the equator (Binford 2001). The Middle Stone Age evidence from Africa therefore assumes considerable importance as an example of lower latitude foraging (though ironically the best evidence comes from extreme southern Africa, which is not tropical). This evidence is also important to the current argument because of its association with anatomically modern humans, at least after 100,000 years ago. Some African evidence resembles that of Europe despite the fact that the tactics of tropical hunters tend to differ from those who live in high latitudes (stalking vs mass kills) (Marean 1997). At the Kenyan site of GvJm46, where undated MSA levels are stratified below LSA levels, 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 Salzgitter-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). Evidence of fishing at Katanda (Yellen et al 1995), and use of corms at Klasies River Mouth (Deacon 1989) attests to the breadth and effectiveness of MSA foraging. However, other evidence suggests that MSA hunters may not have been as effective as those of the LSA. In an environment in which buffalo were common, the MSA hunters at Klasies River Mouth preferred the more docile (and perhaps more easily driven) but less common eland. Moreover, unlike later LSA people who focused on seals only during calving season, the MSA hunters appear to have acquired them opportunistically throughout the year (Klein & Cruz-Uribe 1996). A similar pattern appears to hold for tortoises. Based on this kind of evidence Klein has long maintained that the MSA hunters were less capable than the LSA hunters. Marean counters that the difference between MSA and LSA faunal remains reflects differing population densities, not a difference in effectiveness of hunting (Marean & Assefa 1998, Marean et al 2000).

Gaudzinski and Roebroeks (2000), and McBrearty and Brooks (2000), believe the Middle Palaeolithic and MSA evidence compares well with the evidence from the European LUP, 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. Specialised hunting and reuse of sites implicates 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 Salzgitter-Lebenstedt and GvJm46 attest to very effective hunting tactics, but these were systems that did not require the services of modern EWM. What distinguishes the late European Upper Palaeolithic system is not specialisation *per se*, but the evidence for flexibility, in the guise of the variety of LUP 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.

The archaeological evidence for managed foraging is heavily weighted toward the near past. This may simply reflect the sliding scale of resolution that is a result of differential preservation. The best archaeological examples of managed foraging are, after all, sites and groups of sites with good preservation, extensive data from flotation, and abundant faunal remains. Nevertheless, we believe that the shallow time depth of managed foraging is not just a function of some taphonomic threshold (Bednarik 1994). Over the last twenty five years archaeology has developed an impressive array of techniques for identifying animal exploitation patterns from faunal remains, and faunal remains can survive well for tens of thousands of years. Faunal evidence suggests that European hunters had begun some management practices by the LUP. Similar evidence indicates that the hunters at Salzgitter Lebenstedt, 35,000 years earlier, had not. It is important to reiterate that the record for managed foraging does not map simply onto standard culture-stratigraphic units like Upper Palaeolithic or Later Stone Age. The initial appearance of these techno-cultural units antedates good evidence for managed foraging, which very much appears to have been a late Pleistocene/early Holocene development.

4.2 Independent corroboration for EWM

Thus far we have argued that modern managed foraging depends on EWM, and that managed foraging was itself a relatively late development in human hunting and gathering life-ways. If we wish to make the evolutionary link that EWM enabled the development of managed foraging, we need to establish an independent line of evidence that EWM appeared prior to, or at least contemporaneously with, managed foraging. If evidence for EWM is extremely old, then clearly it would be of minor significance in understanding the advent of managed foraging. On the other hand, if our only evidence for EWM is managed foraging itself, our argument would rest solely on our argument concerning the role of EWM in modern foraging, and would be essentially circular.

Luckily, there is at least one independent line of archaeological evidence that documents EWM earlier than managed foraging. This is the evidence for calculating devices. A calculating device is an artefact

that assists a person in formulating a solution to a problem. It is a kind of cultural algorithm. Examples include personal computers, calendars, divination bones, game tokens, and so on. An algorithm is a set of rules, like arithmetic, that can be used in problem solving. Algorithms depend on the attention window of EWM. Though stored in long-term memory, they are deployed by working memory and rely on EWM's ability to hold multiple inputs at once. Algorithms also enhance EWM. A rule can be held in mind as a simple token (in the phonological store, eg, 'commutative rule'), freeing the thinker from the necessity of reasoning through the relationship anew each time. If an algorithm can be held outside attention altogether, as happens with a calculating device, then EWM becomes much more effective. External algorithms may also free long-term memory storage for more meaningful and relevant material. Information contained in calculating devices may be considered declarative memories (memories for facts). Rote facts may take more effort to store (by repeated trials) and may be more difficult to recall than episodic memories (more meaningful). Thus, calculating devices store information externally that might otherwise take up working memory capacity, freeing consciousness from memorisation and recall. They may also preserve attention to more essential tasks.

The earliest calculating devices are counters. These are pieces of bone, ivory, or antler on which someone had engraved a sequence of marks. Microscopic examination has revealed that, often, different tools had made the marks, at different times (Marshack various, eg, 1985; d'Errico various, eg, 2001). Marshack has described these artefacts as 'time factored', because they were used over several episodes and appear to have been used to count or keep track of something. What that something was remains elusive (days, moons, animals, menstrual cycles), but the key here is that these counters are algorithmic devices, and attest to the use of EWM. The best examples, like the Tai plaque (Marshack 1991) and the Tossal bone (d'Errico & Cacho 1994), date to the late Palaeolithic or Epipalaeolithic, but the example from Blanchard in France is EUP in age, dating to perhaps 28,000 BP.

Earlier engraved bones are provocative but not clearly computational. The engraved bone from Blombos Cave in South Africa dates to perhaps 70,000, making it the oldest generally accepted

engraved object (d'Errico et al 2001). The enigmatic Berekhat Ram object (d'Errico & Nowell 2000) may be four times as old. Neither, however, presents an example of sequential marking made at clearly different times with different tools, and neither is a calculating device. They may be significant for other problems of prehistoric interpretation, but they do not document EWM.

The evidence of calculating devices places EWM in the European EUP, slightly antedating the evidence for managed foraging.

Only one prehistoric fact tempts us to argue for EWM earlier than about 40,000 – the colonisation of Australia. It is the sheer complexity of this accomplishment that led us initially to cite it as an example of executive functions in general (Coolidge & Wynn 2001). Colonisation of the Sahul required an over-the-horizon trip in boats (Davidson & Noble 1992; Davidson 1999); it could not have been an accident. Davidson has argued that the construction of boats and planning of the journey implies the use of modern language. We agree, but rather emphasise the necessity of contingent plans of action. While it remains theoretically possible that humans using only procedural knowledge and some ability to anticipate future states (abilities possessed by all Archaic humans) made the journey, it just seems unlikely that these could have effected a successful colonisation with, apparently, families and dogs. Contingent plans of action would certainly require relatively sophisticated executive functions, and perhaps, EWM. If EWM allowed language a 'flowering of tenses', then the subjunctive mode of speech might have been the vehicle for creating and expressing contingent plans of action. A successful sea voyage would have also undoubtedly required the executive functions of response inhibition, selective attention, and sophisticated organisation, planning, and decision-making. Even conservative estimates place people in Australia prior to 40,000, and some archaeologists favour dates in the 60-70,000 range (Davidson 1999).

5 Conclusion and discussion

We believe that the evidence supports our contention that the evolution of EWM was a key prerequisite to the development of all managed foraging systems. Our specific argument rests on three lines of evidence, as follows.

- 1 All modern subsistence systems depend on the cognitive abilities enabled by EWM, with contingency planning, response inhibition, and the integration of action across time and space being essentially ubiquitous in both agricultural and hunting and gathering systems.
- 2 Archaeological evidence indicates a relatively shallow time depth for managed foraging. Compelling evidence places managed foraging back only to about 12,000 years ago and, although there are reasons for extending the record back to at least 23,000, these earlier archaeological traces lack one tell-tale feature of the later evidence – innovation. Only comparatively weak arguments can be made for managed foraging earlier than this.
- 3 Independent archaeological evidence for EWM corresponds well with the evidence for managed foraging – compelling evidence at 14,000, strong evidence at 28-30,000, and only very weak evidence earlier.

We do not think that the temporal correspondence between EWM and managed foraging can be coincidental. The long ages of the Middle Palaeolithic and Middle Stone Age were monotonous in terms of subsistence. Archaic humans were effective foragers capable of living in a wide range of habitats and exploiting an impressive variety of resources. But they accepted what the habitat offered, they did not manage. The strategy of managed foraging – and it is a strategy, not a tactic – appeared only very late in human evolution, at the same time or soon after the evolution of the EWM upon which it depends. The immediate consequences were important to the adaptive success of modern humans and, probably, their rapid geographic expansion at the end of the Pleistocene (eg, colonisation of the Sahul, the Americas, and eventually Oceania). Managed foraging can respond quickly and effectively to new or changing conditions, providing a flexible set of responses to changing habitats, and the ability to invade new habitats very quickly. The long-term consequences were even more profound. Only a managed foraging system is able to recognise and exploit the potential of domesticated resources, and adopt the strategies necessary for farming.

It is important to reiterate at this point that the picture presented here does not map easily onto the standard units of Eurasian-African culture history.

Good evidence for managed foraging emerges, chronologically, in the middle of the Upper Palaeolithic and Later Stone Age, not at the beginning nor at the end. Indeed, the standard units of palaeo-anthropological interpretation would appear to be largely irrelevant. We cannot, for example, simply conclude that anatomically modern humans endowed with EWM and managed foraging emerged in Africa prior to 100,000 years ago, and expanded to fill the world soon thereafter. EWM and managed foraging appeared far too late to support such an interpretation. We suggest that the evidence supports either of two different, but not mutually exclusive, scenarios.

The first agrees with Klein's argument that behavioural modernity evolved after anatomical modernity (Klein 2000). The mutation or mutations that produced EWM occurred sometime after 100,000 years ago (Klein favours a date as late as 50,000) in southern Africa, after which it spread very rapidly through standard Darwinian mechanisms. The initial selective advantage may have occurred in the domains of language (longer and more complex utterances) and social complexity (an argument favoured by Barkley 2001), but EWM eventually enabled the development of managed foraging. This scenario has the advantage of simplicity. However, its timing, especially Klein's preferred date of 50,000, allows little or no time for behavioural modernity to reach southeast Asia and enable the colonisation of the Sahul. But more importantly, this scenario downplays the role of culture change. Most anthropologists consider modern behaviour, including managed foraging, to be a complex bio-cultural phenomenon, based on cognitive ability and traditional knowledge. As such, a mutation enhancing a cognitive ability does not yield simple, direct behavioural consequences. Its effect must be played out within a cultural context, a fact that informs a slightly different scenario.

In the second scenario the mutation or mutations occurred earlier, perhaps even as early as the evolution of anatomically modern humans, but instead of yielding an immediate behavioural difference, the resulting enhancement of working memory changed the nature of cultural evolution. In particular, EWM enabled innovation and algorithmic thinking, both of which are largely cultural phenomena. Innovation relies on analogy (S Klein 1983), thought experiment (Shepard 1997), and collaborative learning (Tomasello 1993) – all of which are dependent on the

ability of EWM to hold and process multiple inputs simultaneously. But all three utilise existing cultural knowledge as raw material. Innovation in turn powers the 'ratchet effect' (Basalla 1988; Tomasello et al 1993), the cumulative development of cultural knowledge that we associate with modern progressive change. By its nature culture change resulting from the ratchet effect would be mostly invisible in its early stages when there was little cultural raw material on which to work, but it would eventually appear in the archaeological record as accelerating change. Algorithmic thinking consists of sets of rules for solving problems – counting, arithmetic, calendars, etc – and while these depend upon and enhance working memory (see above), they are purely cultural devices, and as such must be invented. As a style of thinking, algorithms almost certainly yielded an evolutionary advantage, but they could not have sprung fully developed along with EWM. There must have been a significant lag time. With the advent of innovation and algorithms, culture entered a new era in which change became essentially Lamarckian in character (Gould 2002) and exponential in effect. The initial consequences would be invisible archaeologically because innovation would initially have been very rare (it is still unusual) and algorithms simple.

However, soon after it achieved the threshold of archaeological visibility, change would appear to be explosive. This is just what the archaeological record shows, including the record for managed foraging.

These two scenarios are not mutually exclusive. The ratchet effect could, for example, be folded into the first scenario (though this would make the colonisation of Australia difficult to explain). However the story is framed, Sherratt appears to have been correct in concluding that a cognitive development preceded and enabled the eventual origin of agriculture. But this development – enhanced working memory – was of more general significance, enabling not just managed foraging and agriculture, but modern culture itself.

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