Recognizing Complex Cognition through Innovative Technology in Stone Age and Palaeolithic Sites

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Cognitive complexity is defined here as the capacity for abstract thought, analogical reasoning, cognitive fluidity, innovative thought, complex goal-directed actions, flexibility in problem-solving, multi-tasking, task switching, response inhibition and planning over long distances or time. Some of these attributes are archaeologically recognizable in transformative technologies such as heat treatment of rocks and ochre, and the manufacture of compound adhesives and paints. Advanced executive functions of the brain are also required for remote capture during snaring, which is implied by circumstantial archaeological evidence. Some technologies seem good indicators of complex cognition and the emphasis here is on making the connection, but this does not mean that cognition necessarily drove innovation in the past any more than it does today. The recursive relationships between cognition, social behaviour and technology mean that change cannot be attributed to a single stimulus.

When did minds resembling ours have their origin? How can we recognize such minds archaeologically? These are simple questions, but they cannot be answered in a straightforward way, and they have increasingly absorbed archaeologists who study Palaeolithic and Stone Age sites. The intellectual tension is almost tangible between researchers who use archaeological evidence to demonstrate that complex cognition developed late in prehistory and those who use the same data to demonstrate an early origin, that is, prior to the Upper Palaeolithic or Later Stone Age. For example, Wynn and Coolidge (2003; 2007a,b; 2009) use a 'Working Memory' model to show that 'executive functions of the brain' and sophisticated technology and behaviour coincide no earlier than in the Upper Palaeolithic. This places the material culture evidence for complex behaviour disconcertingly out-of-line with the chronological evidence for anatomical modernity. Indeed, Zilhão (2007) points out that the 'hardware' for behavioural innovation was in place several hundreds of thousands of years ago when the brain entered its modern range of variation (in size and shape and areas of connectivity). He therefore maintains that the novelties which archaeologists value as indicators of cultural sophistication emerged as part of social and demographic processes, not as the result of genetic or palaeoneurological developments.

The approaches seem polarized, but here I attempt to use the strengths of each argument to move the dialogue forward. I do so with the understanding that carefully constructed bridging arguments are essential between data and theory (Botha 2008) because this approach imposes the rigour necessary to establish scientific credibility. Although I agree with Zilhão's conclusion, I contend that certain innovations are particularly useful for revealing the cognitive capacity of their makers and that the Working Memory Model is suitable for this task. This is because some activities and manufacturing processes demand mental architecture and cognitive capacities like those of living populations. Having said this, it is also likely that social interventions played a pivotal role in deciding when and how innovation took place in the past. This is certainly the case today. Types of social influence most likely fluctuated at different stages of human physical and cognitive development. I defer a discussion of social stimuli for innovation to the end of this article. An important caveat is that it is unwise to single out prime movers for behavioural development (Healy & Rowe 2007) and it is not my intention to do so here. Healy and Rowe suggest that complex behaviours may depend on developed motor skills as well as on cognition and that it is problematic to isolate and focus on particular regions of the brain or particular behaviours.

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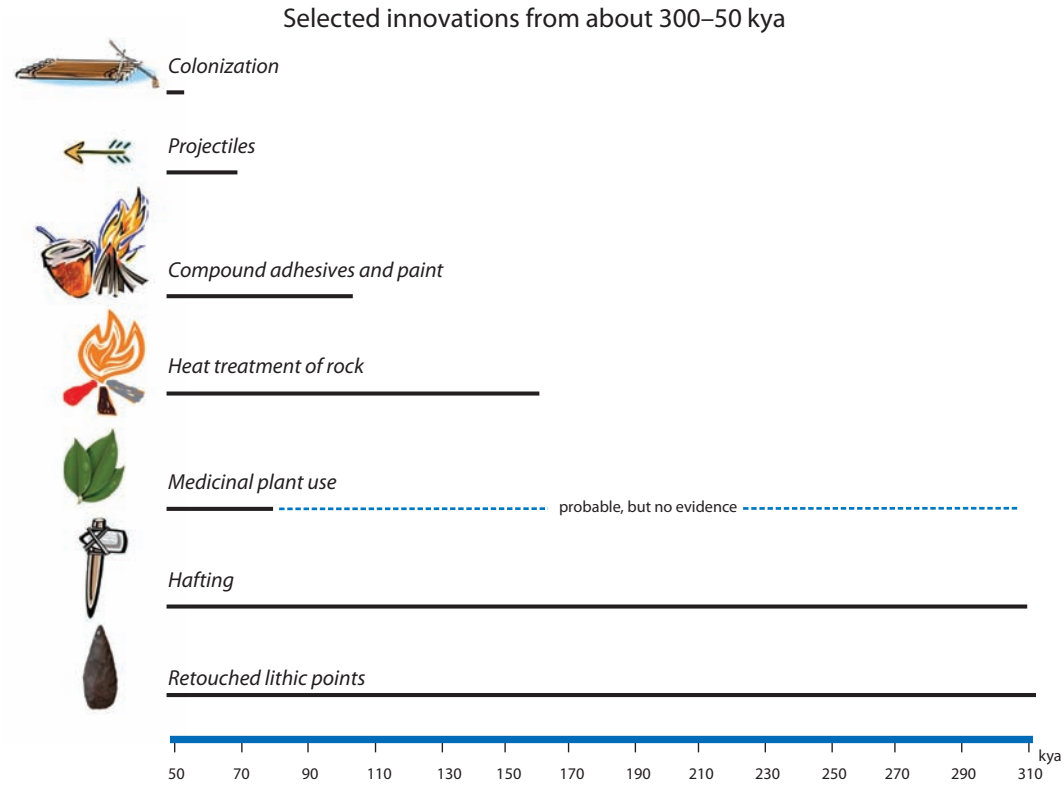


Figure 1. *Selected innovations occurring between about 300 and 50 kya in several parts of the world. Retouched lithic points and hafting may be considerably older than 300 kya. Colonization refers specifically to the circumstantial evidence for the use of watercraft for making ocean crossings.*

Here I adopt the definition of innovation used by Coward and Grove (2011), that is, innovation implies anything that is new to hominin lifeways, for example, an artefact, behaviour, or a form of social organization. Innovations specific to the African Stone Age, and thought to be linked to symbolism, are discussed in more detail in McBrearty and Brooks (2000). I choose to focus on innovations used for everyday tasks. The examples come from Africa, Europe and Asia and they seem to have originated about 100,000 years ago (100 kya) or even before then, for example, heat treatment of rock, and the manufacture of compound mixtures, such as adhesive and paint (Fig. 1). These innovations are especially important because they imply the concept of transformation. Transformative technologies involve the combination of ingredients to create an irreversibly altered end product. Other innovations that are important cognitive indices, though they might lack the concept of transformation, include the introduction of retouched lithic points and hafting of tools, possibly more than 300 kya, medicinal plant use, projectile hunting and colonization (for instance to Australia) through the use of watercraft (Fig. 1). The reason for highlighting these archaeological data will become apparent during the discussion of human cognition.

Ancient sites do not preserve relevant parts of hominin brains, so inferences about complex cognition must be made from behavioural traces or circumstantial evidence. By cognitive complexity I mean a capacity for abstract thought, analogical reasoning, multitasking and 'cognitive fluidity' (Amati & Shallice 2007; Barnard 2010a; Mithen 1996). In addition, I use Wynn and Coolidge's (2003) suggestion that enriched cognitive abilities, called 'enhanced executive functions' of the brain, encompass innovative thought and imply the ability for complex goal-directed actions, flexibility in problem-solving, task switching, response inhibition, and planning over long distances or time.

Abstraction is an essential component of complex cognition. The 'wiring' of brains is partly responsible for this because cortico-basal ganglia circuits play a role in abstract cognitive processes and assist in making choices between several possible behaviours at a given time (Koralek *et al*. 2012). Mithen (1996) used the term 'cognitive fluidity' to refer to connections that are made between mental modules to enable versatile behaviour and innovative technologies, and these will

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be discussed again. The concept is not unlike that used by Wynn and Coolidge (2011) to describe 'fluid intelligence', which is essential for initiating novel behaviours. Innovative technologies that require enhanced executive functions, such as complex goal-directed actions and flexibility in problem-solving, include transformative ones like the alloying of metals and the production of kiln-fired ceramics (Coolidge & Wynn 2006; Wynn & Coolidge 2007a,b). Both technologies combine and transform raw materials, usually irreversibly and, although apprenticeship is often involved, the mental processes required also involve long-range planning and executive functions of the brain that are not needed for simpler, sometimes mundane tasks. These mental processes are different from those used for traditional hunter-gatherer tasks like wooden spear-making, which can be learned exclusively through prolonged apprenticeship (Wynn & Coolidge 2007b). Wooden spear-making does not suggest enhanced executive functions partly because the numbers of cognitive steps required are relatively few compared with those needed, for example, by composite tool production (Haidle 2010). Ambrose (2002) has long argued that composite tool use is linked to people with modern brains. It is not possible, of course, for a cognigram to draw a precise boundary between simple or complex tasks based on the exact number of cognitive steps required for their completion. Instead it is necessary to use a 'sliding scale' in which one task can be seen to be more or less complex than another.

A different executive function, response inhibition, involves suppressing instincts such as eating an entire crop, instead retaining some seed for replanting. Other functions, such as the ability to organize endeavours across space and through time, may entail coordinating procedures with distant, unseen players (Wynn & Coolidge 2003). Both of these executive functions come into play when people set snares: the performance is out-of-sight and carefully planned, but unseen action results in delayed gratification. Presently I shall examine other innovative technologies that require enhanced executive functions such as multi-tasking and analogical thought. I shall also investigate the material culture evidence for the attributes of complex cognition that I have outlined. First, though, I discuss the relationship between cognitive complexity and components of the brain.

Brain functions and complex cognition

Brain functions

To some extent the absolute size of the human brain is relevant to the dialogue about cognitive abilities, even though the modern range was achieved well before the period under consideration. Interpreting brain size in comparative or evolutionary contexts is speculative and problematic (Heesy 2005); nonetheless some size attributes do seem relevant to the development of modern brains. Schenker and colleagues (2005) report that gyral white matter is relatively larger than expected in modern humans, and that this matter can result in connections between cortical areas capable of rapid relaying and processing of information. Complex cognitive function is thereby facilitated. It is also possible to say that brain size increased along with the relative size of specific neural systems. Passive brain growth and increasing body size occur in conjunction with each other, but active brain growth more often results from the selection for greater neural space with better connective arrangements (Aboitiz 2001, 356). Neural connectivity seems fundamental to increased cognitive and behavioural capacity and Amati and Shallice (2007) propose that this took place in part of the prefrontal cortex as the result of a type of brain computation called latching. The prefrontal cortex, located in the front of the brain, is associated with complex behaviours (Aboitiz 2001, 357) and the executive functions listed by Wynn and Coolidge (2003) depend on frontal-lobe-linked capacity. Attention and decision-making are most clearly evident in the executive functions of the frontal lobes, which include our modern tactical ability to plan ahead (Grossenbacher 1996).

Coolidge and Wynn (2001; 2005; Wynn & Coolidge 2003; 2007a,b) also call attention to evidence that executive functions are inheritable and that a genetically transferable, neural mutation could have resulted in increased memory capacity. Mithen (1996) and Klein and Edgar (2002) earlier proposed that a neural mutation could have been responsible for modern thinking. In this regard, an increase of the hormone and neurotransmitter, dopamine, may be partly responsible for increments in neurocognitive functions of the brain in *Homo sapien*s. Dopamine aids essential brain functions such as the flow of information from various regions of the brain to the frontal lobes, and it affects memory, attention and problem-solving (Heijtz *et al*. 2007). Particularly relevant for the period under discussion is the claim by Settle and colleagues (2010) that genetic variability in dopamine transmission may affect the human desire for innovation. This is because the 7-repeat allele of the D_4 dopamine receptor gene is associated with novelty-seeking behaviour. The neurotransmitter plays other roles, too; dopamine neurons learn to encode the long-term value of future rewards for actions (Enomoto *et al*. 2011). Assigning long-term reward values is essential for the successful

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achievement of distant goals (Enomoto *et al.* 2011), something that is indispensible for the attribute of contingency planning, to be discussed later.

While the architecture of the brain sets performance boundaries, the feedback process between brain and behaviour is critical to outputs. We cannot move directly from neural theory to a behavioural one without also drawing on models of mental architecture because the behaviour of the mind is a product of all its components acting together and providing feedback to each other (Barnard 2010a,b). Barnard's (2010a) model of a '9-subsystem mental architecture', which is attributed to people with abilities like ours, involves abstraction arising from the simultaneous mental processing of two levels of meaning. Interactions occur between the two levels of meaning while people talk and act — thus only the most advanced mental architecture, like ours, can multi-task to allow walking, talking and thinking at the same time (Barnard 2010a). Hominins like *Homo erectus*, possibly possessing a 7-subsystem mental architecture system, would not be able to multi-task, though they would be able to communicate, albeit at a level lower than that enabled by 8- or 9-subsystem mental architecture (Barnard 2010a).

I hope to demonstrate that some types of technology imply particular mental capacities because of the cognitive requirements of the tasks at hand. I explore ways to access complex cognition through everyday technologies. In so doing it must be asked whether the identified technologies rely on particular cognitive capacities and that they could not be achieved without these. In applying a 'strict standard', Wynn and Coolidge (2009) insist on cognitive validity: if archaeological traces could have been generated by simple actions, or simple cognition, then the straightforward explanation must be accepted.

In the introduction, I listed some behavioural attributes that imply complex cognition and enhanced executive functions of the brain: planning over long distances or time, response inhibition, and technological transformations that imply a capacity for analogical reasoning, abstract thought, multi-tasking, cognitive fluidity, complex goal-directed actions, flexibility in problem-solving and task switching. I now discuss some of these attributes in more detail and I explain how some classes of archaeological evidence can be proxies for them.

Planning and response inhibition

Planning can include: 1) planning for an operation that will take place within days rather than hours; 2) planning during a technical procedure; and 3) contingency planning. Lithic knapping is a good example of the first and second types of planning. People plan to knap when they collect suitable rocks and they plan successive motions during the execution of knapping. Wynn and Coolidge (2010) analysed the procedures used by a Boxgrove knapper during biface manufacture. While working, the knapper carefully planned the blows, and monitored the process for usable flakes, in other words, Wynn and Coolidge suggest that the knapper simultaneously held two separate goals in mind. Gesher Benot Ya'aqov (GBY), in Israel, is an even older Acheulean site than Boxgrove, and Goren-Inbar (2011) argues that deep planning is evident here in the production sequence of bifaces and their by-products. As at Boxgrove, the GBY knapper evaluated each individual blow as part of the planning sequence. Flexibility was shown in evaluating each blow, then selecting one striking method from the known and varied Acheulean repertoire (Goren-Inbar 2011).

Ambrose (2010) suggests that composite tool manufacture may have coevolved with the anterior frontal lobe and the capacity for complex planning. He advocates that these developments took place at around 300 kya and that they were shared by *Homo sapiens* and Neanderthals. This noteworthy conclusion implies, controversially, that some aspects of complex cognition are not owned by *Homo sapiens* alone. The emphasis on the importance of composite tools as one marker of cognitive development is well-founded because composite artefact manufacture would, as Ambrose (2010) suggests, have placed demands on constructive memory. The archaeological evidence, a few examples of which are given below, seems to support his conclusion that composite tools appeared hundreds of thousands of years ago and that they continued to play an important role for hunter-gatherers thereafter. It is necessary, though, to distinguish hafting methods because not all of them are equally intricate and therefore equally taxing from a cognitive point of view. Binding a tool to a shaft with twine seems reasonably straightforward (though it is a more complex action than making a single component tool) and the method allows for mending or re-cycling of the composite tool. The addition of a bonding agent increases the complexity of the task. A recent claim for hafting at *c.* 500 kya has been made at Kathu Pan, South Africa (Wilkins *et al*. 2012), but the relationship between the dated geological horizon and the hafted tools remains to be satisfactorily demonstrated. In contrast, the K4 bedded tuffs of the Kapthurin Formation, Kenya, are securely dated to 285–235 kya, and they yielded small bifacial points (Tryon & McBrearty 2006) that were presumably designed to be hafted as inserts

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on weapons. Basal trimming of points suggests that they were thinned in order to facilitate attachment to shafts. Small points thought to have been hafted have been found elsewhere in East Africa (Brooks *et al.* 2006). Backed (blunted) tools, dating to about 300 kya, are part of the Lupemban Industry of Twin Rivers in Zambia (Barham 2002; Clark & Brown 2001). Backed tools are often parts of composite implements and in this case they may be associated with fossil remains of *Homo rhodesiensis* (elsewhere called *Homo heidelbergensis*) at Kabwe, also in Zambia (Barham 2002). If these archaic humans were indeed the makers of the backed tools (and the association is not certain), and if the tools were indeed hafted, then we have an intriguing situation whereby three species, *Homo sapiens*, *Homo rhodesiensis* and *Homo neanderthalensis* (discussed below), created composite tools whose manufacture and use required elaborate planning and considerable skill.

Based on use-wear analyses, some tool classes, for example percussion tools like core-axes, appear to have been hafted in northeast Africa immediately after the end of the Acheulean, from the Sangoan onwards (Rots *et al.* 2011). Optically Stimulated Luminescence ages from Sai Island, in the Nile Valley of Sudan, where core-axes were hafted, are between 182±20 and 223±19 kya (Van Peer *et al.* 2004). However, these might be minimum ages for the northeast African Sangoan assemblages. The embryonic hafting technology seems to have been relatively uncomplicated, without glue, so it may have involved the use of bindings such as sinew or bark twine. Hunting projectile weapons that also seem to have an early origin may have involved the use of shafts with stone inserts that were attached with binding material.

Contingency planning is used here to imply behaviour that involves response inhibition. Investing labour upfront for future returns is both contingency planning and response inhibition, and the long-range strategies require advanced executive functions of the brain. Contingency planning and response inhibition are entailed in specific preparation techniques to render poisonous or indigestible plant foods edible, or to make careful use of poisonous plants for medicine. At Niah Cave, Sarawak, Borneo, the collection and processing of toxic plants for consumption between about 46 and 34 kya is implied by sediment scorching, and the recovery of pollen, palynomorphs, phytoliths, plant macrofossils and starch grains (Barker *et al*. 2007). At Sibudu, South Africa, aromatic leaves of *Cryptocarya woodii* (a taxon that has insecticidal properties) seem to have been intentionally collected at 77 kya, and laid on sedge bedding to repel insects (Wadley *et al*. 2011). Charred wood from a Euphorbiaceae tree, probably the Tamboeti, *Spirostachys africana*, was recovered from a few hearths in 58 kya Middle Stone Age layers at the site (Allott 2006). Smoke from *S. africana* is toxic, causing severe headaches and nausea, and diarrhoea if food is accidentally cooked over a fire using the wood (Watt & Breyer-Brandwijk 1962, 436). Such smoke would certainly have a knock-down effect on insects, indeed even the wood of Tamboeti can be stored amongst clothing to keep away insects (Watt & Breyer-Brandwijk 1962, 436). The absence of familiar plant foods and medicines cannot be underestimated as a challenge for people who undertook migrations. The colonization of Australia is thus an example of exceptional planning and risk-taking of the kind associated with people like us (Davidson 2010). Ability to transfer knowledge from known to unknown circumstances suggests that the migrants (Bowler *et al*. 2003; Veth *et al.* 2011) were either expecting their new environment to be similar to the old, or they were confident in their ability to extract resources from unfamiliar terrain. On the one hand, it seems possible that people were capable of abstracting properties of subsistence strategies from their former environment and transposing those on to their new land. On the other hand, trial and error must have been part of the process of colonization. One potential proxy for this is the rate at which a continent like Australia was colonized. Assuming an initial population of 20, and a final population 50,000 years later of 2,000,000, the rate of increase is tiny (0.0001 or 0.01 per cent) (Davidson 2013). The implied rate of movement is thus 0.370 km yr^{-1} (Davidson 2013), suggesting that the adaptation process to the new continent might not have been either quick or easy.

A good example of contingency planning together with response inhibition is snaring, which requires complex executive functions of the brain. Making a snare obliges a person to hold in mind actions that are out-of-sight, and it also enforces response inhibition by obliging the hunter to wait for the meat to come to him/her. The hunter has to strategize accordingly. Adaptable social circumstances are enabled through the invention of the snare, which can be set and tended easily by people of all ages. Snares may have been used at Sibudu in the Howiesons Poort, *c.* 65 kya (Wadley 2010a), because the fauna of the time is dominated by tiny blue duiker that dwell in forests together with the remains of many small carnivores (Clark & Plug 2008) that are susceptible to being caught in snares.

Contingency planning is also a requirement for the transformative technologies that I now describe.

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Transformative innovations

Some technical strategies seem dependent on particular cognitive abilities, and indeed cannot be carried out in their absence. Transformative processes require enhanced executive functions of the brain so they are a fitting place to search for the link between complex cognition and culture. Transformative technologies often combine raw materials ingeniously to create synthetic products that exemplify the modification of nature by culture. Alloying of metals and firing of ceramics were previously mentioned because these are good examples of natural products permanently transformed. Comparable transformative technologies that predate metal working and ceramics include deliberate heat treatment of rock or ochre, and the creation of compound adhesives and other compound products. All these processes have in common the use of pyrotechnology (see for example Bentsen 2012).

Careful experiments are required to highlight the range of knowledge and informed decision making required by the people using transformative technology in the past. It is largely through experiments that it is possible to infer the cognitive processes involved in particular technical processes. When natural products are experimented with, for example, rock (including ochre) and plant materials such as wood or gums, the properties of the products must be investigated and reported. This is because geological attributes cause rocks and ochre to behave in particular ways when they are heated, knapped or ground. Similarly, wood from individual taxa burn with different temperatures, length of burning and amounts of ash produced. Gum viscosity varies, too. Furthermore, plant gum does not behave in the same way as resin.

Deliberate heat treatment of materials and compound adhesive manufacture are ideal examples of transformative, innovative technology and they provide proxies for complex cognition. The processes are discussed in turn.

Heat treatment of siliceous rocks

Clearly the term 'heat treatment' is only applicable when the strategy of heating is deliberate, and when rocks are heated in a controlled manner, prior to or during one or other stage of the knapping process (Mercieca 2000). I first describe experimental heat treatment conducted by Domański and colleagues (2009) with flint, and by Purdy and Brooks (1971) with Florida cherts, then I introduce silcrete. Domański and colleagues (2009) heated pieces of flint experimentally in a laboratory oven. A peak temperature of 400°C was achieved and held for two hours; then the rocks were cooled slowly in the closed oven. One set of experimental flints was buried 3 cm deep in a sand bath, the other left open in the oven. When expansion and contraction are rapid, fractures occur explosively (Purdy & Brooks 1971), and Domański and colleagues (2009) also found that a high frequency of uncovered specimens exploded in the oven during heating. Burial in sand in anoxic conditions reduced the differential expansion that causes rock to explode. Siliceous rocks, such as chert and flint, remain undamaged when heated to 300°C and 400°C, but rapid cooling or heating, or temperatures above 400°C, produce brittleness and/or microcracking because of the high coefficient of thermal expansion of the quartz in siliceous rocks. Rapid cooling or heating are inevitable in field-based fires where, as I shall explain later, the ramp rate can be as rapid as 500°C within the first five minutes of lighting the fire.

The structural changes to heat-treated siliceous rocks are accompanied by changes in lustre and sometimes by changes in colour. The flaked surfaces of heat-treated rocks frequently have a greasy lustre that is in contrast to the dull outer surface of unworked rock (Purdy & Brooks 1971). Darkening in colour may take place if the rock contains some iron, for example, colour may change from yellow or yellow-brown to deep red. Purdy and Brooks (1971) maintain that, during heating, the quartz crystals in siliceous rocks recrystallize; this is said to occur when the melting point of the impurities within the intercrystalline spaces is reached thereby allowing the microcrystals to fit closer together than they did before heating. The change promotes even-grained textures and intergranular fractures that require less energy for their formation than intragranular ones (Purdy & Brooks 1971). However, Schmidt and colleagues (2012) maintain that recrystallization does not take place when siliceous rocks are heated. Their results imply, instead, that heating leads to a loss of silanol (SiOH) and the creation of new Si–O–Si bonds, a reaction that begins between 200°C and 300°C and causes increased hardness in heated siliceous rocks (Schmidt *et al.* 2012). Schmidt and colleagues (in press) also demonstrate that 'pore-closing', which plays a role in improving flaking properties of silcrete, probably by increasing the fine-grained nature of the rock, takes place between 400°C and 500°C.

Knappers who used heat-treated rocks in the past may have known little about the processes involved, but they clearly knew that suitable heating made siliceous rocks relatively easy to knap. The conditions created by heating and cooling affect the usefulness of heat treating siliceous rocks. The flints that Domański and colleagues (2009) buried in sand, then subjected

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to slow heating and cooling, exhibited substantial reduction in fracture toughness (fracture toughness is measured in joules/mm^2 when fracture is initiated). Less energy was thus required to knap flakes from these rocks than was the case prior to heating. Heating techniques also affect the strength of siliceous rocks as measured by tests of compressive strength and point tensile strength (measured in pressure units of atm [the 'standard atmosphere']). When Purdy and Brooks heated chert specimens, then removed them immediately from the oven without first allowing them to cool down, the cherts exhibited a 40 per cent reduction of strength over unheated samples. However, when cherts were allowed to cool gradually in the oven after heating, they generated increased strength of 25 to 40 per cent over unheated cherts (Purdy & Brooks 1971).

At Pinnacle Point the thermomagnetic history of silcrete shows that all of the tested archaeological samples (n = 12) from PP5–6 and the Still Bay biface from Blombos Sands had been heated. The samples had a single heating component with maximum temperatures between 300° to 400°C (Brown *et al.* 2009), which is exactly the range of temperatures found to be ideal in Purdy and Brooks's experiments with chert. Brown and colleagues (2009) experimented with silcrete and found that thin bifacial points could be knapped with a higher success rate on heated than unheated silcrete. Furthermore, changes wrought to siliceous rocks during controlled heat treatment can facilitate fine pressure flaking (Cotterell & Kamminga 1992; Domański & Webb 1992; Mourre *et al*. 2010; Webb & Domański 2009). Pressure flaking is a retouching technique used by knappers to shape a stone artefact by exerting pressure close to its edge using the narrow end of a retouching tool (Mourre *et al*. 2010). Pressure flaking often produces invasive flaking scars and tools with thin working edges. Mourre and colleagues (2010) replicated pressure flaking on silcrete and they commented that this flaking technique was only successful after the preforms were heat treated. The technique was once considered to be an Upper Palaeolithic innovation dating to *c.* 20 kya, but the new studies show that pressure flaking occurred on Middle Stone Age silcrete tools recovered from the *c.* 75,000-year-old levels at Blombos Cave, South Africa (Mourre *et al.* 2010), and from *c.* 72,000-year-old levels at Pinnacle Point, South Africa (Brown *et al.* 2009). At Blombos, silcrete Still Bay bifacial points are said to have been heat treated prior to pressure flaking in the final knapping phase (Mourre *et al*. 2010), so the pieces heated would have been fairly small compared to the size of the original cores. This raises the issue of the size of rocks chosen for heat treatment. The size variable seems as important to rocks as the temperature variable is to fires.

Mercieca and Hiscock (2008) advocate that heating strategies necessitated knowledge of the thermal responses of the rocks being treated, as well as the appropriate temperatures that could be used. They demonstrate that slow and steady heat treatment under anaerobic conditions is not always necessary, and that heating of rocks can sometimes be carried out in aerobic conditions if the pieces to be heated are small enough (Mercieca & Hiscock 2008). This is because large items fracture at lower temperatures than small ones, which have higher cracking and fracture thresholds. Increasing specimen size reduces the resistance of the rock to heat fracturing when suddenly exposed to heat (Mercieca 2000). The term 'heat fracturing' describes the physical stresses (in the form of such fractures as crenation, potlidding and surface crazing) produced by heat, regardless of whether this was intentional or accidental (Mercieca 2000). Lithic blanks or preforms can be controlled for size more accurately than can temperature during the heating event (Mercieca & Hiscock 2008), thus knappers can exercise some control over the outcomes of the heating process through standardizing rock-specimen size. Mercieca and Hiscock used differently sized silcrete pieces to demonstrate their point: they cut experimental blocks into 10 × 10 × 10 mm (1 cm^3) for the smallest cubes and 40 × 40 × 40 mm (64 cm^3) for the largest cubes. The 64 cm^3 cubes were more susceptible than the small cubes to undesirable fracture during increases of temperature. The temperature above which unwanted fracturing occurred in the small silcrete cubes varied from 700°C to 900°C, but it was lower for the larger blocks. While it seems that knappers might be able to use simple, open fires to heat treat the tiniest pieces of rock, it is clear that doing this with larger blanks would be risky, notwithstanding the suggestion by Schmidt and colleagues (in press) that South African silcrete can be treated in a simple way on an open fire or in coals scraped from such a fire. An added complication when heating a relatively large block of silcrete, even if it does not explode, is that water is not easily evacuated from its centre and heat treatment can be unsuccessful as a result (Schmidt *et al*. in press).

For all these reasons, the production of pressure-flaked bifaces such as those found in the Still Bay at Blombos (Mourre *et al*. 2010) seems to have required heating of pre-shaped tools. The gloss study of the Blombos tools shows that preforms, not cores, were heated. The preforms would have been somewhat longer (though thinner) than the largest blocks heated by Mercieca and Hiscock (2008).

Most experiments (save those by Brown *et al*. 2009) to heat treat rocks have been conducted in

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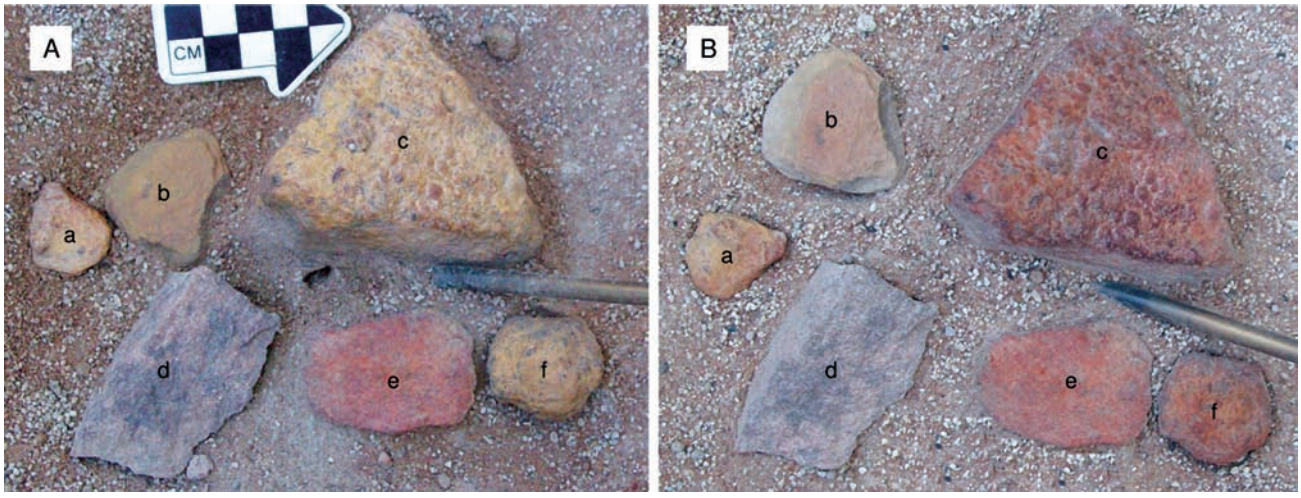


Figure 2. *Ochre pieces and sandstone roasted 5 cm underground shown (left) before heating and (right) after heating. The colour change from yellow to red is still unmistakable on the ochre pieces that were originally yellow (a, b, c and f), but the grey sandstone (d) did not change colour. The ochre piece that was originally red (e) did not change colour. The metal thermoprobe is visible to the right of each picture.*

laboratory furnaces. This is sometimes appropriate because it reduces variables and enables consistent outcomes. However, the artisans who heat treated rocks in the past had to deal with precisely those variables caused by differing conditions of firewood, weather, soil moisture content, and the rocks themselves. Depending on the variables, which are often not predictable, an open fire may reach its maximum temperature within five minutes, 50 minutes or longer. The ramp rate of an open fire is rapid and it is therefore risky to place items for heat treatment directly into an open fire. Such action seems untenable when rocks are collected from distant sources and much time is invested in the production of blanks for heating. It makes more sense that heat treatment of rock by people in the past would have involved burying rocks below the ground surface, lighting a fire or placing coals on sand above the buried rocks, and then allowing the rocks to heat and cool slowly before excavating them for use. The same process may have been used for treating ochre.

Heat treatment of ochre

In a different application of pyrotechnology, iron-rich rocks can be heated to transform their colour from yellow or orange to red. As with heat treatment of rocks for knapping, the heating of ochre involves planning, patience and considerable expertise and understanding of the properties of all the natural products involved.

The term ochre is colloquially used for any ferruginous rock containing iron oxide or iron oxyhydroxide. Red ochre is generally haematite (α-Fe_2O_3) with a red to red-brown streak and a hexagonal crystal system (Schwertmann & Cornell 1991). Yellow ochre is generally goethite (α-FeOOH), which is a hydrated iron oxyhydroxide with an orthorhombic crystal system. When heated to about 350°C, goethite dehydroxylates simultaneously with colour change from yellow or orange-brown to red (Cornell & Schwertmann 2003). Heated and unheated ochre can be distinguished because changes take place to the crystal structure of the goethite and these can be recognized using X-ray diffraction (Helwig 1997). Haematite produced as a result of heating goethite gives a diffraction pattern referred to as 'disordered haematite' (Helwig 1997).

Ochre has a long history of use in Africa, the Near East and Europe. Its collection and use dates to almost 300 kya in Africa (Barham 2002; McBrearty 2001). Red ochre was used in Europe by Neanderthals as early as 250–200 kya (Roebroeks *et al*. 2012), although manganese dioxide, a black mineral, seems to have been more often used by these hominins (d'Errico 2008). Red is the most regularly recorded colour of ochre pieces recovered from southern African MSA sites (Henshilwood *et al*. 2009; Hodgskiss 2012; Watts 1997) including sites older than *c.* 160 kya, such as Pinnacle Point (Marean *et al.* 2007). At Sibudu, ochre is present in a number of forms from 77 kya to more recently (Hodgskiss 2012). It is most common at 58 kya where it occurs either as unmodified pieces, ground nodules with striations, or as patches of ground powder on cemented hearths, deposits on sandstone slabs, and as residues on stone tools (Lombard 2005; 2007; 2011;

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Wadley *et al*. 2009; Wadley 2010a,b,c). The Ndwedwe shale quarry, from which some of the Sibudu ochre was collected, contains abundant red as well as yellow nodules, so heat treatment of yellow ochre solely to change its colour seems unlikely at this site, unless the act of transforming the colour of the material was part of ritual behaviour. This scenario is feasible, but at present the hypothesis does not seem to be falsifiable. Future ochre-heating experiments are needed to explore the possibility that ochre attributes apart from colour are beneficially affected by heat treatment.

The results of several field experiments (Wadley 2009; 2010d) demonstrate that ochre colour is transformed by relatively low temperatures when nodules are buried under fireplaces (Fig. 2).

One experiment is described briefly here; details about the natural products used are elsewhere (Wadley 2010d). Ochre pieces were buried 5 cm and 10 cm under a fire lit from *Acacia erioloba* wood and some ochre pieces were also placed on the surface within the fire's flames. The fire temperature rose to 500°C within five minutes, but the maximum underground temperatures (296°C at 10 cm below surface and 430°C at 5 cm below surface) were reached far more slowly, about 19 hours after the fire was lit (Fig. 3). At 10 cm below surface, temperatures of >200°C were maintained for 10¾ hours. At 5 cm below surface, temperatures >300°C were maintained for 13¼ hours and temperatures *c.* 400°C for 5½ hours (Wadley 2010d). The rapid heating of the fire caused explosive fracturing of the ochre that lay on the ground surface (and this ochre did not change colour), whereas 5 cm and 10 cm below surface, where the sand heated and cooled slowly, the ochre was perfectly preserved, and orange and yellow pieces became red. The experiments demonstrate that colour transformations can take place, not only as the result of deliberate heat treatment, but also post-depositionally and therefore accidentally. This makes the recognition of deliberately heated ochre extremely difficult in sites where combustion features are common and where the rake-out of hearths probably occurred regularly.

One archaeological example where deliberate heat treatment of ochre seems convincing is in the Levant at Qafzeh where two ochre lumps, dated to between 100 and 92 kya, were subjected to thermoluminescence to identify heat treatment. They seem to have been heated and transformed to haematite because of the thermal activation characteristic of the 110°C thermoluminescence peak of quartz grains extracted from the samples (Godfrey-Smith & Ilani 2004). The authors think that the heating took place deliberately to alter the colour of ochre to a desirable shade of red. Red ochre is in short supply in the

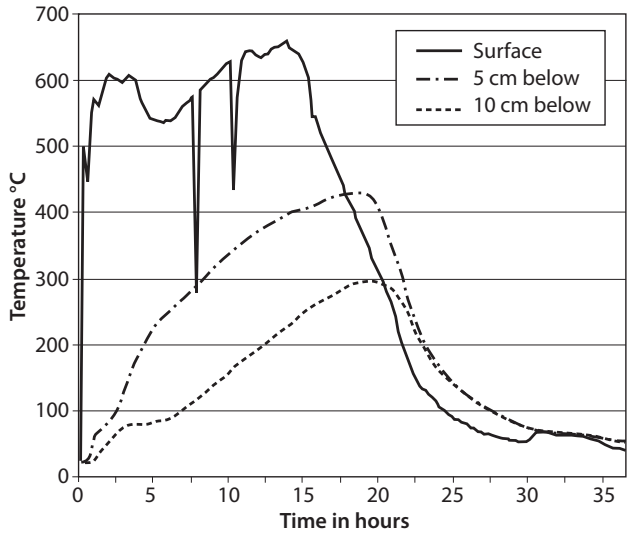


Figure 3. *Temperatures recorded in an experimental fire using 9.2 kg of* Acacia erioloba *wood. Temperatures (°C) were recorded on the ground surface, 5 cm below surface, and 10 cm below surface, and were measured every 15 minutes for 36 hours. A temperature of 500°C was reached within 5 minutes.*

Qafzeh area, so the transformation of yellow to red seems appropriate if the colour red was particularly desirable in the past. In the absence of evidence for utilitarian use of ochre, Hovers and colleagues (2003) suggest that it played a symbolic role at Qafzeh, not least because ochre was prominently associated with human burials. Another investigation into putative heat treatment was carried out on four pieces of ochre from Es-Skhul, Israel, which has age estimates between 135 and 100 kya (d'Errico *et al*. 2010). The ochre was studied using optical microscopy, Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Energy Dispersive X-ray (EDX), X-ray microdiffraction (m-XRD), Particle-Induced X-Ray Emission Spectrometry (PIXE) and Proton-Induced Gamma-ray Emission (PIGE) (d'Errico *et al*. 2010). SEM/EDX analysis identified iron-rich calcium phosphate in two specimens, potassium-rich clay with titanium-rich iron oxide inclusions in the third specimen, and pure iron oxide crystals in the fourth specimen. TEM/EDX and m-XRD analysis demonstrate that one piece was unheated, but that three pieces were heated to at least 300°C, and that the process dehydrated goethite into haematite, and changed the yellow colour to orange or red (d'Errico *et al.* 2010).

The Middle Palaeolithic site Bečov I, northwest Bohemia is attributed to Marine Isotope Stage (MIS) 7 (200–250 kya) (Šajnerová-Dušková *et al.* 2009). Four grinding stones used to rub and mix pigments and

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numerous fragments of porcellanite of various shades of yellow, orange or red were recovered. Some of the rocks bear traces of heating and use (Šajnerová-Dušková *et al.* 2009), so there is a possibility that heat treatment began long before 100 kya, but more details about the site are required to justify this conclusion.

Cognitive implications of deliberate heat treatment

Adjudicating between deliberate heat treatment and accidental heating of geological products is not straightforward. Post-depositional hearth use and consequent heating of buried items can burn and alter them (Asmussen 2009; Pierce *et al*. 1998; Sievers & Wadley 2008) and, while it is possible to identify heated ochre and some types of heated rock, assigning intention is problematic. There is always the possibility that some worked lithics that display heating are recycled artefacts that were accidentally heated (Vaquero *et al*. 2012), so the issue must be approached cautiously.

In cases where heat treatment is deliberate, the artisan must make some important decisions in order to achieve the appropriate temperatures necessary to roast rocks or ochre to the point of transformation, but not destruction. First is the decision of whether to use the high-risk option of roasting on an open fire. Schmidt and colleagues (in press) advocate that this technique was appropriate for silcrete. It could result in successful heat treatment if fire temperatures were controlled and modulated, and if the lithic products placed in the fire were small. Even so, there is a chance that rocks heated in this way could fracture prematurely or explode. If the option of heating on an open fire is rejected, then a strategy for underground heating must be devised. The artisan must devise a mental algorithm based on the above-ground performance of the fire. The reducing environment underground is a more reliable and controlled environment than the oxidizing situation above ground where fire temperatures are uninhibited, and may ramp rapidly causing rocks to explode. However, the type and amount of a chosen wood type influence both the above-ground temperatures and the length of burning of the fire and these factors, together with sediment particle size and depth below surface, determine the below-ground temperatures. Underground temperatures could not be measured directly by people who lived in the Middle Stone Age or Middle Palaeolithic, and the effects of heating on the rocks or ochre would have been hidden from sight. Thus a form of analogical reasoning seems necessary for the above-ground and underground heating relationship to be successful. It is true that the concept of underground heating of rocks may have been originally discovered accidentally through rake-out of disused fireplaces. Nonetheless, the repeated success of such transformation when it is deliberately undertaken implies achieving specific temperatures that are appropriate for the product being heated. At present I cannot think of a way to adjudicate between the accidental and deliberate heating of ochre. Siliceous rocks that have been heated and subsequently knapped are easier to recognize than heated ochre because the surfaces of heated rocks have a dull patina before knapping. After knapping the freshly exposed surfaces exhibit a distinct gloss that can be quantitatively measured (Brown *et al*. 2009).

Analogical reasoning of the kind needed for conducting underground heating is the *sine qua non* of modern executive functions (Wynn *et al*. 2009). Such analogical reasoning is more easily recognized in artworks that combine features of one entity with those from a different content domain. Well-known archaeological examples include the 'man-lion' figurine from Hohlenstein-Stadel, Germany (Wynn *et al*. 2009), and the therianthrope (a figure that is part human and part animal) painted on a rock slab from Apollo 11, Namibia (Wendt 1976). Both of these examples are, of course, much younger than the heat treatment of rocks or ochre that took place in the Middle Stone Age and Middle Palaeolithic. They are also much younger than the heated compound adhesives and paints that have been found in Middle Stone Age sites.

Glues, compound adhesives and compound paints

I use the term 'glue' to mean a single-component plant or geological product usually requiring no preparation (for example plant gum like *Acacia* gum that has nothing added and is usually not heated). Its use is relatively uncomplicated, but if combined with binding it creates a number of steps in the manufacturing process of composite tools. Ethologists might argue that glue is made by several birds and spiders that weave intricate nests or webs and that there is nothing special about human use of glue. However, animal actions are instinctive and they are not directly comparable with human ones. Animals use simply-coded operational sequences in which the distances between problems and solutions are small (Haidle 2010). Another important difference between human and animal glue processing is the human use of pyrotechnology, without which the preparation of some glues would not be possible. Natural plant gum contains polysaccharides, is soluble in water, is often 'runny' and may require some heating to dry it. Resin, like gum, is a plant derivative, but it is chemically different from plant gums, and it contains volatile fluid terpenes. Some resins or products containing resin, such as bitumen, are natural ingredients

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(Cârciumaru *et al.* 2012) formed from organic materials subjected geologically to heat and/or pressure (Boëda *et al.* 1996). Bitumen can be used as simple glue with no prior extractive treatment required although the lumps may need heat to soften them. Other glues, such as birch-pitch, require controlled heat treatment for their extraction (see for example, Pawlik & Thissen 2011), but pitch is still considered 'glue' because it is a single component fixative.

The addition of glue to facilitate hafting is likely to have begun more recently than the process of hafting with binding agents. One of the main incentives for the use of glue is that it enables flexible arrangements of lithic inserts on shafts or handles (Rots 2002), and it enables complicated composite tool manufacture. The first glues may have been materials such as bitumen (a geological product), or plant gums and resins. Bitumen and birch-bark tar were used in the Mousterian of Europe and the Near East. Neither requires other ingredients to be added to them, but in the case of bitumen, some geological types naturally contain a coarse-grained component that acts as a successful aggregate for bonding agents. For example, bitumen cobbles found in the Bichri Massif, Syria, formed as a result of the disaggregation of tar sand, so these cobbles contain quartz grains (Boëda *et al.* 2008). Although both bitumen and birch-bark tar are strictly 'simple glues', they require heat treatment using exacting protocols, so their production is sophisticated. Mousterian stone tools from Umm el Tlel, Syria, have traces of bitumen on their surfaces in positions consistent with hafting. These have been dated to 71–72 kya (Boëda *et al.* 2008), but it is not known which hominin was responsible for the hafted tools. Two stone flakes partly covered in birch-bark tar were discovered in central Italy in fluvial gravel and clay associated with Middle Pleistocene fauna that may pre-date MIS 6 (Mazza *et al*. 2006), and at Gura Cheii-Râşnov Cave, Romania, bitumen was found on stone tools belonging to the Upper and Middle Palaeolithic (Cârciumaru *et al*. 2012). At Inden-Altdorf, Germany, birch-pitch residues were found on Micoquian tools, suggesting that hafted multi-component tools were made in the Middle Palaeolithic, at about 120 kya (Pawlik & Thissen 2011). Thus the practice of using bitumen or birch-bark tar for bonding agents was widespread, and its use was not exclusively by *Homo sapiens*. At Königsaue, Germany, birch-bark tar was used more than 45 kya by Neanderthals for hafting of stone knives. GC-MS analyses of two organic pieces of the tar revealed the presence of betulin, a triterpenoid from the lupane family that is particularly abundant in white birch bark (Regert 2004). It was also established that the glue was produced through a several-hour-long smouldering process under anoxic conditions, and at controlled temperatures of between 340 and 400°C (Koller *et al.* 2001; Regert 2004). Neanderthals had mastered pyrotechnology in order to create this useful raw material. Zilhão (2007) suggests that the Königsaue pitch could not have been developed, transmitted and maintained in the absence of abstract thinking and language as we know them. Abstract thought is one of the attributes of enhanced working memory. At the very least, the pyrotechnology described seems to require enhanced working memory, the acquisition of which, according to Coolidge and Wynn (2005), is the hallmark of our own modern cognition. This example is one reason why Zilhão (2007) claims that the emergence of behavioural complexity is not a species-specific phenomenon, but that the genetic and cognitive basis for complex behaviours must have been present in the genus *Homo* before the evolutionary split between Neanderthal and modern human lineages.

The term 'adhesive' implies, here, that the product comprises more than one ingredient, that it has been transformed to a synthetic bonding agent, and that the process cannot be reversed to take apart and recreate the original ingredients. A complicated process is generally required for the making of adhesives, and their use is therefore cognitively more demanding than that required by other means of assembling components for composite tools, including the collection and use of glue.

Replication of compound adhesives (Wadley *et al*. 2009) and their use for hafting demonstrates the complexity of the process. Manipulation of ingredients such as plant gum and powdered iron oxide is demanding because the flexibility of plant gum, the aggregate-size of ochre powder, and the heat of fires are inconsistent attributes that require different quantities and processing procedures for each adhesive-manufacturing event. After attaching lithic inserts to their hafts with the moist adhesive, the assembled tools must be dried near a fire, using controlled heat to prevent the adhesive from burning or seeping. During the entire process, the artisan must pay close attention to method, must multi-task, and be prepared to switch a course of action at the last minute. Such actions are cognitively difficult for people even today, so the making of compound adhesives provides circumstantial evidence for complex cognition and enhanced working memory (Wadley *et al*. 2009).

The earliest evidence in north Africa for the use of a compound adhesive for hafting may be in MIS 5 at Taramsa 8, Egypt, where a foliate had potential resin residues and red stains that might be iron oxide traces from a compound adhesive (Rots *et al.* 2011; Van Peer *et al*. 2008). From the beginning of the Nubian

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Complex onwards (early MIS 5), hafted knives were used at Sodmein Cave, Egypt, and, in the late Nubian Complex (late MIS 5) of this site, thrusting spear elements (from ME93/413/52) have proximal notches that might be intentional adjustments for hafting (Rots *et al.* 2011). Other tools such as scrapers were hafted in the late Middle Stone Age at Sai 8-B-11, Sudan. Several of the northeast African late Middle Stone Age (MIS 4/3) tools have ochre traces that are interpreted as remnants of the adhesive used for hafting (Rots *et al*. 2011). Ochre was visible on several implements at Sai 8-B-11 as well as on tools from Sodmein. One large, broken Levallois flake from Sodmein has a clear ochre band that appears on the dorsal and ventral face in a position consistent with the placement of adhesives for hafting. Another flaked tool from Sodmein has ochre in association with potential resin residues (Rots *et al.* 2011). An important observation is that some tools are hafted even when hafting is not a necessity for their use (Rots *et al*. 2011). This implies that, as seems to have been the case with the heat treatment of rocks, there was a decoupling of productive strategies and technical need.

At Rose Cottage and Sibudu, South Africa, Middle Stone Age tools were hafted with compound adhesives that involved a variety of recipes, for example, ochre mixed with plant gum, or plant gum mixed with fat (Lombard 2007; 2011; Wadley *et al.* 2004; 2009). Ochre-loaded adhesive was used at Sibudu by at least 70 kya and at Rose Cottage by about 65 kya (Wadley *et al*. 2004; 2009; Wadley 2010c). Brown and colleagues (2012) suggest furthermore that hafted microliths were part of the 71 kya assemblages at Pinnacle Point 5–6, South Africa, but residues from adhesives have not been recorded there.

Brooks and colleagues (2006) suggest that small points imply the existence of complex projectile technology in the Middle Stone Age. Arrows may have their origin in the Middle Stone Age (Lombard & Phillipson 2010) and any such projectile technology would be facilitated by adhesives. Compound adhesives are strong bonding agents that can be used in the absence of bindings. Such a stand-alone commodity is indispensable for tools such as segments (also known as crescents) (Fig. 4) which have straight cutting edges that would sever binding unless notches were produced on their cutting edges. It is the manner in which compound adhesives are used with segments that provides an extra layer of information about the cognitive powers of the artisans. Lombard (2007; 2011) examined hafting traces, including adhesive residues, on segments from Sibudu. She was able to demonstrate that, between 65 and 62 kya, Sibudu's Howiesons Poort segments were hafted transversely,

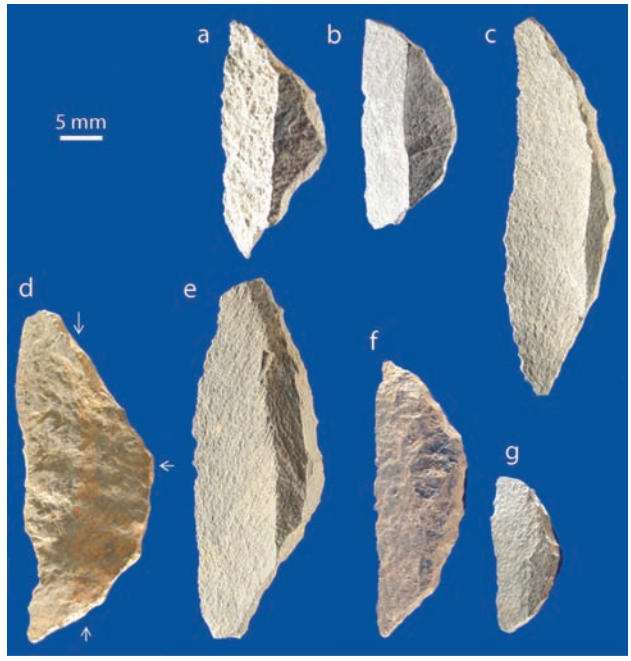


Figure 4. *Segments from the Howiesons Poort occupations dating 65–62 kya at Sibudu. Segment d has traces of ochre on its lateral, marking where the compound adhesive once attached the tool to its haft. The red ochre occurs on half the surface of the segment between the arrows. Segments a, d and f are made on dolerite and the rest are made on hornfels.*

longitudinally or diagonally. A variety of tool types thus resulted from the rotation of a single tool class (Wadley 2010c). This action is not to be confused with the related ability that apes have to twist a fruit to break its stem; in this scenario, the hand and fruit turn as muscles control the postures correlated the visual changes (Barnard 2010b). In contrast, mental rotation used for hafting segments requires abstract visualization of the various angles needed to place and fix the same class of tool at different angles. This operation implies enhanced working memory, and psychologists use complex span tasks, including mental rotation exercises, to measure cognitive capacity (Kane *et al.* 2004). Task performance is linked to cognitive competences such as attention span, executive function and complex reasoning (Kane *et al*. 2004). One complex-span task requires a person to rotate a letter of the alphabet mentally, or to make a decision about a shape's symmetry on either side of a vertical axis (Engle 2010; Kane *et al.* 2004). This task is not unlike that of rotating a stone tool in its haft. The use of adhesive to allow the unconstrained hafting of tools at a variety of angles is ingenious. However, since so much of human behaviour seems designed to impress other

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humans rather than to seek economic productivity (for example, Hawkes & Bliege Bird 2002), it is possible that the Howiesons Poort technical innovations were also socially driven.

At Blombos Cave a remarkable find was made in a 100,000-year-old occupation; two large marine shells were used to store a compound, ochre-rich, liquid (Henshilwood *et al*. 2011). The ochre-rich compound comprises ochre powder, crushed bone, charcoal fragments, quartz and quartzite micro-debitage, and these ingredients were mixed with an unknown liquid. Henshilwood and colleagues favour the interpretation that the 100,000-year-old liquid was paint. The shells were accompanied by a toolkit for manufacturing the paint on site. The purpose of the compound liquid can be debated; it can be argued that experiments are needed to test the appropriateness of the liquid as paint versus adhesive. However, ochre-rich compounds have several potential applications, and the purpose of this particular compound is not key to the present argument. What is more important is that it provides complementary evidence for the production of compound products that have been found at other Middle Stone Age sites. The manufacture of compounds at 100 kya confirms that people of the time had complex cognition because such manufacturing processes required multi-tasking and thinking in abstract terms about the qualities and necessary quantities of the ingredients that were manipulated. Making compounds of any kind implies complex cognition, as I demonstrated earlier, and we can come to this conclusion without knowing what the compounds were used for. The compounds transform their ingredients irreversibly to a new product. It is tempting to speculate that people capable of these technical transformations were also capable of using them as metaphors for social transformations (Wadley 2013). It could even be argued that social need arose prior to the inventions discussed here. Indeed, this is possible because aspects of human social behaviour interact in a recursive and positive way with the brain. Sociability and working-memory capacity have been linked in a recent study where it was found that people who engage extensively in social activities perform better on tests of cognitive performance that include working-memory capacity (Ybarra *et al.* 2008). This supports a hypothesis that social factors may have been implicated in developments *en route* to complex cognition.

The social stimulus for innovative technologies

The 'social brain hypothesis' is that our social lives drove complex behaviour and even encephalization, and that there is a quantitative relationship between social group size (at the community, not band level) and the neocortex volume of the brain (Dunbar 2003). The social brain hypothesis is about social complexity, not just about group size (Gamble *et al.* 2011). The hypothesis consequently espouses a relationship between demography and behaviour, for example, dispersed communities whose members keep only infrequent contact may present considerable cognitive demands because the needs of absent members must be constantly borne in mind (Gamble *et al*. 2011). However, sharing of information via extended social exchange networks is also critical because it enables advanced planning and exploitation of culturally constructed niches (Ambrose 2002). A universal amongst hunter-gatherers studied during historic times is the practice of aggregation and dispersal, sometimes using seasons as the cue. Large band size during aggregation facilitates sharing of information and this social phase also seems to correlate with a wider range of material culture items than the dispersal phase (Wadley 1987). The incentive to innovate is therefore likely to be high when groups coalesce and artefacts may be 'formal' or 'showy' when people try to impress others. This proposition accords with the 'show-off' hypothesis (Hawkes & Bliege Bird 2002) that men use hunting methods that bring them public acclaim even when those methods are economically risky and costly in terms of time and energy.

The moment of technological invention may then be the serendipitous combination of appropriate cognitive abilities, suitable environment and perceived social need. I argue, as others have before me, that social factors may ultimately be the prime mover. Gamble (2007) is adamant that technologies are always social constructs, that technology is not so much about problem-solving as about identity, and that we should consequently try to understand social activities and relationships. Once innovation is in progress, an interactive situation may occur between social perception and innovation, resulting in multiple advances in a short period because successful innovations encourage further such developments. The exponential growth of ground-breaking technology in our own time is an extreme example, yet such escalation is not a foregone conclusion; ebb and flow seem a natural part of development so that an exclusively linear analysis of technology is inappropriate. Once novel behaviour emerges, it may seem inconceivable to us that it might disappear again if the innovation was successful, but there are nonetheless times when material evidence for novelty is highly visible and other times when it seems absent. Pettitt (2011b) questions our surprise, and asks why we expect that such behaviours should be cumulative? Bar-Yosef

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and Kuhn (1999) point to the lack of correlation between novel blade technologies, Upper Palaeolithic industries, and anatomically modern humans because blade technology was known in Eurasia and Africa in the late Lower and the Middle Palaeolithic. They rightly claim that there is no justification for linking technology *per se* to aspects of hominin anatomy or behaviour (Bar-Yosef & Kuhn 1999). There is not a straightforward relationship between human capacity (either mental or physical), social relationships and the desire to innovate. As another example, Moore (2010) reasons that cognitively modern people sometimes knap stone in ways similar to those of non-modern people, with the result that tool manufacture does not necessarily reflect the maximum abilities of hominins at any given stage. Hovers and Belfer-Cohen (2006) appropriately call a paper describing traits allegedly associated with modern behaviour in the Middle Palaeolithic 'Now you see it, now you don't'. They suggest that instability of demographic systems and repeated population reductions inhibited the continuous accumulation of certain items of material culture so that innovations were repeatedly re-invented during the Middle Palaeolithic.

After approximately 160 kya the evidence for innovative technologies disappears and reappears; in part this seems due to the scarcity of sites dated earlier than about 80 kya and d'Errico and Stringer (2011) suggest that there may have been discontinuities in cultural transmission. Such fluctuations do not imply erratic human abilities, but rather perceived social need or the lack thereof. Coward and Grove (2011) claim that behavioural flexibility results in innovation principally within a social group and that innovation is fundamental to other social adaptations, such as increasingly cooperative reproduction. They suggest that innovation cannot be adaptive unless it is linked to adequate social transmission of the new behaviour. They attribute demographic factors to the development of both social learning and innovation and this interpretation has support from previous research (Shennan 2001; Powell *et al*. 2009). Shennan (2001) and Powell and colleagues (2009) find that there is a positive correlation between elevated levels of innovation and demography, rather than with cognition. Shennan (2001) links the waxing and waning of innovation to demographic changes. When group size is small, there is low probability that innovations will be generated or retained because they seem to be of little advantage for small groups. Demographic increases, or even aggregations of formerly remote groups, might stimulate innovation. This idea was developed farther by Powell and colleagues (2009). They are adamant that demography determines the introduction and continuation of cultural complexity. Furthermore, they argue that variation in the density and/or mobility of regional subpopulations results in spatially specific accruals of expertise. Genetic estimates of population size establish that early Upper Palaeolithic Europe and sub-Saharan Africa had similarly high densities when so-called 'modern behaviour' first appeared and skills seem to have increased in concert with interactions between subpopulations. Powell and colleagues (2009) conclude that the appearance, continuation, spread and loss of innovations are influenced by the size and number of subpopulations, and the extent of communication between them. They hypothesize that by about 100 kya population size in Africa may have reached a density and level of interaction between groups that enabled innovations to accumulate at a faster rate than they were lost. This stimulated cultural change in the Middle Stone Age to the extent that it even benefited the survival rate of individuals and their groups (Powell *et al*. 2009). The feedback mechanism that resulted would have encouraged further population increase and intensified group interaction. The model helps to explain not only the rise of innovation at about 100 kya, but the apparent disappearance of some innovations in southern Africa between about 90 and 70 kya, and also the time lag between the appearance of physically modern characteristics in *Homo* and behavioural advances. The hypothesis of Powell and colleagues is significant because it provides a convincing explanation for the emergence and loss of innovations without invoking hominin speciation as a prime mover.

Zilhão (2011) also claims that the emergence of ornaments and art was stimulated by a combination of demographic growth and an intensification of social networks, perhaps over long distances. This, he suggests, is because the ethnographic record shows that objects conveying information about personal and social identity are targeted at strangers or people infrequently met.

Marquet and colleagues (2012) distinguish two main types of innovation: first, technology that is economically driven and, secondly, innovations associated with the ideological world. The emphasis in this article has been on technical innovation. In the Stone Age/Palaeolithic context, technology includes a variety of tools and weapons and the components used to assemble them, whereas the category of innovations relating to ideas, and possibly beliefs, includes ornaments such as perforated shells and novel artefacts such as engraved shell, bone, ivory and ochre and carved implements. Superficially, the two classes of innovation seem to be unrelated, but this is not the case because material culture, behaviour,

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economic strategies and ideology must be viewed holistically within human culture. A simple example of the inseparability of belief and economic systems is encapsulated in Magdalenian spearthrowers carved from antler into stylized animals. Rare artworks and ornaments found in African Stone Age and European Palaeolithic contexts provide us with unmistakable evidence of social and ideological meaning, even when these cannot be easily decoded. I briefly look symbolic material culture that is part of the class of ideological innovation.

Artefacts and spatial contexts that are incontrovertibly carriers of symbolic meaning are rare before the Upper Palaeolithic or Later Stone Age. This means that the material culture evidence for symbolism is disconcertingly out-of-line with the chronological evidence for anatomical modernity. Artefacts like beads and engravings made on ostrich eggshell, stone or ochre are significant cultural markers and they represent new behaviour from at least 100 kya onwards (for example, Henshilwood *et al*. 2002; 2009; Texier *et al*. 2010), but they are preserved at few sites at this early date. Tantalizing evidence for even earlier engravings comes from Lower and Middle Palaeolithic sites, such as Bilzingsleben, Tata, Bacho Kiro, Temnata, Quneitra and Qafzeh, but further research needs to be conducted on these pieces before their relevance can be ascertained (d'Errico *et al*. 2003).

Symbolic material culture can be linked to social complexity more readily than can other types of archaeological evidence. Symbolism and ritual have the potential for reflexive relationships with the brain, thereby enhancing cognition. Ritual behaviour stimulates those parts of the brain associated with working memory and inhibition, in particular the dorsolateral prefrontal cortex and anterior cingulate cortex (Rossano 2009), so once again there is evidence for a feedback situation between human behaviour and brain development. It is a challenge to find ritual in Middle Palaeolithic and Middle Stone Age sites, though symbolism is elusive, too, not least because of the theoretical problems associated with defining symbolic material culture (Wadley 2001). Some archaeologists consider burial to be appropriate evidence (Belfer-Cohen & Hovers 1992), yet Pettitt (2011a) points out that the link has seldom been defended; consequently it is hard to adjudicate between ritual burial acts and a more prosaic use of space to inter the dead. One of the most commonly cited examples of symbolically endowed artefacts is that of 'beads' that may have been worn or used in other ways as media for communication, perhaps to mark group or individual identity. Perforated shells appear to have been manipulated and strung: many have convincing wear facets in their perforations, and some are ochre-covered or burned (for example, Bar-Yosef Mayer *et al.* 2009; Bouzouggar *et al*. 2007; d'Errico *et al*. 2008; 2009; Henshilwood *et al*. 2004; Vanhaeren *et al.* 2006). Kuhn and Stiner (2007) propose that, at the very least, the appearance of beads implies that social information and identities were longer lasting and more structured than previously. They advocate, further, that these durable and exchangeable items might have been used for communication across large areas or even generations, and they may have necessitated higher-order executive functions.

Cognitive interpretations of past behaviour that are biased towards the appearance of symbolic behaviour by anatomically modern humans are popular, but they embody some inconveniences. First, there is increasing evidence to suggest that *Homo sapiens* may not have been the only hominin to practise symbolism or complex forms of technology. For this, as well as for reasons listed by Shea (2011), the expression 'cultural modernity' should be avoided. I prefer the term 'complex cognition' because it carries with it no connotations about hominin taxa, nor does it imply the presence or absence of symbolism. Secondly, a focus on symbolism is limiting because the cognitive implications of material culture items are seldom explored in depth once they are assumed to be embodied with symbolism. Worked ochre is one case in point. Ochre can provide convincing evidence for complex cognition over and beyond its role in the symbolic realm (Wadley *et al*. 2009), but studies of ochre sometimes stop at the point when the word 'symbolism' is mentioned. Thirdly, when symbolic artefacts are awarded primacy, other facets of technology are relegated less attention so that their potential for revealing attributes of complex cognition is compromised. This is regrettable because, as I demonstrated earlier, some aspects of everyday technology hold valuable information about cognitive complexity and perhaps social behaviour. Furthermore, everyday tasks often leave traces that preserve better in archaeological sites than evidence for symbolism.

Final thoughts on complex cognition and transformative innovations

Analysis of everyday tasks can bring us close to understanding the minds of people who used specific technologies. What all the artefacts and technologies discussed earlier have in common is the concept of transformation. Transformative technology in archaeological sites provides useful circumstantial evidence for complex cognition. In each set of case studies it is clear that such technologies involve the fashioning

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of separate ingredients into an entirely new material; the end product is irreversibly altered so that it bears little resemblance to its former individual components. Compound adhesive manufacture offers a good example of a transformative technology that reveals an artisan's ability to multi-task and switch tasks. These abilities are attributes of complex cognition. Heat treatment is an apt example of a transformative technology that involves not only analogical thought, but also response inhibition, organization across space and time, contingency planning, mental rehearsal and thought experiment — all attributes that Wynn and Coolidge (2009) attribute to enhanced executive functions of the brain. Although Mourre and colleagues (2010) demonstrate that silcrete cannot be pressure flaked without heat treatment, heat treatment and pressure flaking of rocks is not a technical necessity for producing other kinds of effective tools. At Sibudu, for example, stone knappers created well-shaped segments (crescents) and Still Bay bifacial points from rocks like hornfels and dolerite that were not heat treated, and which would not have been responsive to heat treatment because of their geological histories. Accordingly, when heat treatment and pressure flaking unquestionably occur (and as explained earlier, there is some debate about whether the process was necessarily complex), they provide examples of decoupling technical need and production method. The type of work satisfaction that results from such decoupling of technology from need connects the social realm with that of technology. Cultural need may have driven technological innovation in the past, as is also the case today.

People who were capable of the technical transformations described here probably also had concepts of cultural transformation. This suggestion provides a potential novel link between social and technological behaviour, and the topic is worthy of future research. At the beginning of the article I pointed to the tensions between, first, researchers who conclude that a late achievement of complex cognition was the prime mover for the introduction of innovations and, secondly, those who claim that social and demographic stimuli were key because human cognitive hardware was in place well before the innovations themselves. A satisfactory resolution rests, in part, on satisfactory definitions of innovation and complex cognition. If the innovations considered to be important for complex cognition are limited to items such as ornaments and engravings, then there is no way to break the deadlock. The debate seems best served by temporarily putting aside the rare items that are often considered to be symbolic. Instead I suggest scrutinizing innovative technological processes involved in the creation of everyday items that were used in the Middle Stone Age and Middle Palaeolithic. This can be done by taking the attributes thought to indicate complex cognition (enhanced working memory in the Wynn and Coolidge terminology), and with the use of bridging theory and experiments that replicate the appropriate technology, linking cognitive attributes to the appropriate technologies. The approach, outlined in this article, suggests that the two perspectives need not be as polarized as they initially seemed. I have shown that cognitive attributes that we recognize in ourselves, for example, analogical reasoning and the ability to multi-task, were needed for tasks such as making compound adhesives and heat treating rocks or ochre. Although secure chronologies are notoriously difficult to obtain in the Middle Stone Age and Middle Palaeolithic, it does appear that some of the innovations I describe here may have their origin at the beginning of both these phases. My aim has been simply to demonstrate how complex cognition can be inferred from transformative technologies, but, in the long term, conclusions reached here have implications for the way that Neanderthals will be judged in comparison with *Homo sapiens.* That discussion goes beyond the scope of this article.

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References

Aboitiz, F., 2001. Size and complexity of the brain in human evolution, in *Humanity from African Naissance to Coming Millennia,* eds. P.V. Tobias, M.A. Raath, J. Moggi-Cecchi & G.A. Doyle. Florence: Firenze University Press, 355–9.

Allott, L.F., 2006. Archaeological charcoal as a window on palaeovegetation and wood-use during the Middle

https://doi.org/10.1017/S0959774313000309 Published online by Cambridge University Press

Stone Age at Sibudu Cave. *Southern African Humanities* 18(1), 173–201.

Amati, D. & T. Shallice, 2007. On the emergence of modern humans. *Cognition* 103, 358–85.

Ambrose, S.H., 2002. Small things remembered: origins of early microlithic industries in sub-Saharan Africa, in *Thinking Small: Global Perspectives on Microlithization*, eds. R.G. Elston & S.L. Kuhn. *Archeological Papers of the American Anthropological Association* Special Issue 12(1), 9–30.

Ambrose, S.H., 2010. Coevolution of composite-tool technology, constructive memory, and language implications for the evolution of modern human behavior. *Current Anthropology* 51(Supplement 1), S135–47.

Asmussen, B., 2009. Intentional or incidental thermal modification? Analysing site occupation via burned bone. *Journal of Archaeological Science* 36(2), 528–36.

Bar-Yosef, O. & S.L. Kuhn, 1999. The big deal about blades: laminar technologies and human evolution. *American Anthropologist* 101(2), 322–38.

Bar-Yosef Mayer, D.E., B. Vandermeersch & O. Bar-Yosef, 2009. Shells and ochre in Middle Paleolithic Qafzeh Cave, Israel: indications for modern behavior. *Journal of Human Evolution* 56(3), 307–14.

Barham, L., 2002. Backed tools in Middle Pleistocene central Africa and their evolutionary significance. *Journal of Human Evolution* 43(5), 585–603.

Barker, G., H. Barton, M. Bird *et al*., 2007. The 'human revolution' in lowland tropical Southeast Asia: the antiquity and behavior of anatomically modern humans at Niah Cave (Sarawak, Borneo). *Journal of Human Evolution* 52(3), 243–61.

Barnard, P.J., 2010a. From executive mechanisms underlying perception and action to the parallel processing of meaning. *Current Anthropology* 51(Supplement 1), S39–54.

Barnard, P.J., 2010b. Current developments in inferring cognitive capabilities from the archaeological traces left by stone tools, in *Stone Tools and the Evolution of Human Cognition*, eds. A. Nowell & I. Davidson. Boulder (CO): University Press of Colorado, 207–26.

Belfer-Cohen, A. & E. Hovers, 1992. In the eye of the beholder: Mousterian and Natufian burials in the Levant. *Current Anthropology* 33(4), 463–71.

Bentsen, S.E., 2012. Size matters: preliminary results from an experimental approach to interpret Middle Stone Age hearths. *Quaternary International* 270, 95–102.

Boëda, É., J. Connan, D. Dessort *et al*., 1996. Bitumen as a hafting material on Middle Palaeolithic artefacts. *Nature* 380, 336–8.

Boëda, É., S. Bonilauri, J. Connan *et al*., 2008. New evidence for significant use of bitumen in Middle Palaeolithic technical systems at Umm El Tlel (Syria) around 70,000 BP. *Paléorient* 34(2), 67–83.

Botha, R., 2008. Prehistoric shell beads as a window on language evolution. *Language and Communication* 28(3), 197–212.

Bouzouggar, A., N. Barton, M. Vanhaeren *et al*., 2007. 82,000-year-old shell beads from North Africa and implications for the origins of modern human behavior. *Proceedings of the National Academy of Sciences of the USA* 104(24), 9964–9.

Bowler, J.M., H. Johnston, J.M. Olley *et al*., 2003. New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421, 837–40.

Brooks, A.S., L. Nevell, J.E. Yellen & G. Hartman, 2006. Projectile technologies of the African MSA: implications for modern human origins, in *Transitions before the Transition: Evolution and Stability in the Middle Paleolithic and Middle Stone Age*, eds. E. Hovers & S.L. Kuhn. New York (NY): Springer, 233–55.

Brown, K.S., C.W. Marean, A.I.R. Herries *et al*., 2009. Fire as an engineering tool of early modern humans. *Science* 325, 859–62.

Brown, K.S., C.W. Marean, Z. Jacobs *et al*., 2012. An early and enduring advanced technology originating 71,000 years ago in South Africa. *Nature* 491, 590–93.

Cârciumaru, M., R.-M. Ion, E.-C. Nițu & R. Stefănescu, 2012. New evidence of adhesive as hafting material on Middle and Upper Palaeolithic artefacts from Gura Cheii-Râşnov Cave (Romania). *Journal of Archaeological Science* 39(7), 1942–50.

Clark, J.D. & K.S. Brown, 2001. The Twin Rivers Kopje, Zambia: stratigraphy, fauna, and artefact assemblages from the 1954 and 1956 excavations. *Journal of Archaeological Science* 28(3), 305–30.

Clark, J.L. & I. Plug, 2008. Animal exploitation strategies during the South African Middle Stone Age: Howiesons Poort and post-Howiesons Poort fauna from Sibudu Cave. *Journal of Human Evolution* 54(6), 886–98.

Coolidge, F.L. & T. Wynn, 2001. Executive functions of the frontal lobes and the evolutionary ascendancy of *Homo sapiens*. *Cambridge Archaeological Journal* 11(2), 255–60.

Coolidge, F.L. & T. Wynn, 2005. Working memory, its executive functions, and the emergence of modern thinking. *Cambridge Archaeological Journal* 15(1), 5–26.

Coolidge, F.L. & T. Wynn, 2006. Recursion, Phonological Storage Capacity, and the Evolution of Modern Speech. Unpublished paper presented to the Cradle of Language Conference, November 2006, Stellenbosch, South Africa.

Cornell, R.M. & U. Schwertmann, 2003. *The Iron Oxides: Structure, Properties, Reactions, Occurrences and Uses*. Weinheim: Wiley-VCH.

Cotterell, B. & J. Kamminga, 1992. *Mechanics of Pre-industrial Technology*. Cambridge: Cambridge University Press.

Coward, F. & M.J. Grove, 2011. Beyond the tools: social innovation and human evolution. *Paleoanthropology* 2011, 111–29.

Davidson, I., 2010. The colonization of Australia and its adjacent islands and the evolution of modern cognition. *Current Anthropology* 51(Supplement 1), S77–89.

Davidson, I., 2013. Peopling the last new worlds: the first colonisation of Sahul and the Americas. *Quaternary International* 285, 1–29.

Domański, M. & J. Webb, 1992. Effect of heat treatment on siliceous rocks used in prehistoric lithic technology. *Journal of Archaeological Science* 19(6), 601–14.

https://doi.org/10.1017/S0959774313000309 Published online by Cambridge University Press

Domański, M., J. Webb, R. Glaisher, J. Gurba, J. Libera & A. Zakościelna, 2009. Heat treatment of Polish flints. *Journal of Archaeological Science* 36(7), 1400–1408.

Dunbar, R.I.M., 2003. The social brain: mind, language, and society in evolutionary perspective. *Annual Review of Anthropology* 32, 163–81.

Engle, R.W., 2010. Role of working-memory capacity in cognitive control. *Current Anthropology* 51(Supplement 1), S17–26.

Enomoto, K., N. Matsumoto, S. Nakai *et al*., 2011. Dopamine neurons learn to encode the long-term value of multiple future rewards. *Proceedings of the National Academy of Sciences of the USA* 108(37), 15,462–7.

d'Errico, F., 2008. *Le rouge et le noir*: implications of early pigment use in Africa, the Near East and Europe for the origin of cultural modernity. *South African Archaeological Society Goodwin Series* 10, 168–74.

d'Errico, F. & C.B. Stringer, 2011. Evolution, revolution or saltation scenario for the emergence of modern cultures? *Philosophical Transactions of the Royal Society B* 366, 1060–69.

d'Errico, F., C. Henshilwood, G. Lawson *et al*., 2003. Archaeological evidence for the emergence of language, symbolism, and music — an alternative multidisciplinary perspective. *Journal of World Prehistory* 17(1), 1–70.

d'Errico, F., M. Vanhaeren & L. Wadley, 2008. Possible shell beads from the Middle Stone Age layers of Sibudu Cave, South Africa. *Journal of Archaeological Science* 35(10), 2675–85.

d'Errico, F., M. Vanhaeren, N. Barton *et al*., 2009. Additional evidence on the use of personal ornaments in the Middle Paleolithic of North Africa. *Proceedings of the National Academy of Sciences of the USA* 106(38), 16,051–6.

d'Errico, F., H. Salomon, C. Vignaud & C. Stringer, 2010. Pigments from the Middle Palaeolithic levels of Es-Skhul (Mount Carmel, Israel). *Journal of Archaeological Science* 37(12), 3099–110.

Gamble, C., 2007. *Origins and Revolutions: Human Identity in Earliest Prehistory*. Cambridge: Cambridge University Press.

Gamble, C., J. Gowlett & R. Dunbar, 2011. The social brain and the shape of the Palaeolithic. *Cambridge Archaeological Journal* 21(1), 115–35.

Godfrey-Smith, D.I. & S. Ilani, 2004. Past thermal history of goethite and hematite fragments from Qafzeh Cave deduced from thermal activation characteristics of the 110°C TL peak of enclosed quartz grains. *Revue d'Archéométrie* 28, 185–90.

Goren-Inbar, N., 2011. Culture and cognition in the Acheulian industry: a case study from Gesher Benot Ya'aqov. *Philosophical Transactions of the Royal Society B* 366, 1038–49.

Grossenbacher, P.G., 1996. Consciousness and evolution in neocortex, in *Modelling the Early Human Mind*, eds. P. Mellars & K. Gibson. (McDonald Institute Monographs.) Cambridge: McDonald Institute for Archaeological Research, 119–29.

Haidle, M.N., 2010. Working-memory capacity and the evolution of modern cognitive potential: implications from animal and early human tool use. *Current Anthropology* 51(Supplement 1), S149–66.

Hawkes, K. & R. Bliege Bird, 2002. Showing off, handicap signaling, and the evolution of men's work. *Evolutionary Anthropology* 11(2), 58–67.

Healy, S.D. & C. Rowe, 2007. A critique of comparative studies of brain size. *Proceedings of the Royal Society B: Biological Sciences* 274(1609), 453–64.

Heesy, C.P., 2005. What are four trillion neurons really good for? *Evolutionary Anthropology* 14(6), 238–9.

Heijtz, R.D., B. Kolb & H. Forssberg, 2007. Motor inhibitory role of dopamine D1 receptors: implications for ADHD. *Physiology and Behaviour* 92(1–2), 155–60.

Helwig, K., 1997. A note on burnt yellow earth pigments: documentary sources and scientific analysis. *Studies in Conservation* 42(3), 181–8.

Henshilwood, C.S., F. d'Errico, R. Yates *et al*., 2002. Emergence of modern human behavior: Middle Stone Age engravings from South Africa. *Science* 295, 1278–80.

Henshilwood, C., F. d'Errico, M. Vanhaeren, K. van Niekerk & Z. Jacobs, 2004. Middle Stone Age shell beads from South Africa. *Science* 304, 404.

Henshilwood, C.S., F. d'Errico & I. Watts, 2009. Engraved ochres from the Middle Stone Age levels at Blombos Cave, South Africa. *Journal of Human Evolution* 57(1), 27–47.

Henshilwood, C.S., F. d'Errico, K.L. van Niekerk *et al*., 2011. A 100,000-year-old ochre-processing workshop at Blombos Cave, South Africa. *Science* 334, 219–22.

Hodgskiss, T., 2012. Attribute analysis of the Sibudu Middle Stone Age ochre assemblage. *Southern African Humanities* 24, 99–120.

Hovers, E. & A. Belfer-Cohen, 2006. "Now you see it, now you don't" — modern human behavior in the Middle Paleolithic, in *Transitions before the Transition: Evolution and Stability in the Middle Paleolithic and Middle Stone Age*, eds. E. Hovers & S.L. Kuhn. New York (NY): Springer, 295–304.

Hovers, E., S. Ilani, O. Bar-Yosef & B. Vandermeersch, 2003. An early case of color symbolism: ochre use by modern humans in Qafzeh Cave. *Current Anthropology* 44(4), 491–522.

Kane, M.J., D.Z. Hambrick, S.W. Tuholski *et al*., 2004. The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General* 133, 189–217.

Klein, R.G. & B. Edgar, 2002. *The Dawn of Human Culture.* New York (NY): John Wiley & Sons.

Koller, J., U. Baumer & D. Mania, 2001. High-tech in the middle Palaeolithic: Neandertal-manufactured pitch identified. *European Journal of Archaeology* 4(3), 385–97.

Koralek, A.C., X. Jin, J.D. Long II, R.M. Costa & J.M. Carmena, 2012. Corticostriatal plasticity is necessary for learning intentional neuroprosthetic skills. *Nature* 483, 331–5.

Kuhn, S.L. & M.C. Stiner, 2007. Body ornamentation as information technology: towards an understanding of

https://doi.org/10.1017/S0959774313000309 Published online by Cambridge University Press

the significance of early beads, in *Rethinking the Human Revolution: New Behavioural and Biological Perspectives on the Origin and Dispersal of Modern Humans*, eds. P. Mellars, K. Boyle, O. Bar-Yosef & C. Stringer. (McDonald Institute Monographs.) Cambridge: McDonald Institute for Archaeological Research, 45–54.

Lombard, M., 2005. Evidence for hunting and hafting during the Middle Stone Age at Sibudu Cave, KwaZulu-Natal, South Africa: a multianalytical approach. *Journal of Human Evolution* 48(3), 279–300.

Lombard, M., 2007. The gripping nature of ochre: the association of ochre with the Howiesons Poort adhesives and Later Stone Age mastics from South Africa. *Journal of Human Evolution* 53(4), 406–19.

Lombard, M., 2011. Quartz-tipped arrows older than 60 ka: further use-trace evidence from Sibudu, KwaZulu-Natal, South Africa. *Journal of Archaeological Science* 38(8), 1918–30.

Lombard, M. & L. Phillipson, 2010. Indications of bow and stone-tipped arrow use 64,000 years ago in KwaZulu-Natal, South Africa. *Antiquity* 84, 635–48.

Marean, C.W., M. Bar-Matthews, J. Bernatchez *et al*., 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature* 449, 905–8.

Marquet, P.A., C.M. Santoro, C. Latorre *et al*., 2012. Emergence of social complexity among coastal hunter-gatherers in the Atacama Desert of northern Chile. *Proceedings of the National Academy of Sciences of the USA* 109(37), 14,754–60.

Mazza, P.P.A., F. Martini, B. Sala *et al*., 2006. A new Palaeolithic discovery: tar-hafted stone tools in a European Mid-Pleistocene bone-bearing bed. *Journal of Archaeological Science* 33(9), 1310–18.

McBrearty, S., 2001. The Middle Pleistocene of East Africa, in *Human Roots: Africa and Asia in the Middle Pleistocene*, eds. L. Barham & K. Robson-Brown. Bristol: Western Academic & Specialist Press, 81–97.

McBrearty, S. & A.S. Brooks, 2000. The revolution that wasn't: a new interpretation of the origin of modern human behavior. *Journal of Human Evolution* 39(5), 453–63.

Mercieca, A., 2000. Burnt and broken: an experimental study of heat fracturing in silcrete. *Australian Archaeology* 51, 40–47.

Mercieca, A. & P. Hiscock, 2008. Experimental insights into alternative strategies of lithic heat treatment. *Journal of Archaeological Science* 35(9), 2634–9.

Mithen, S., 1996. *The Prehistory of the Mind: a Search for the Origins of Art, Religion and Science*. London: Thames & Hudson.

Moore, M.W., 2010. 'Grammars of action' and stone flaking design space, in *Stone Tools and the Evolution of Human Cognition*, eds. A. Nowell & I. Davidson. Boulder (CO): University Press of Colorado, 13–43.

Mourre, V., P. Villa & C.S. Henshilwood, 2010. Early use of pressure flaking on lithic artifacts at Blombos Cave, South Africa. *Science* 330, 659–62.

Pawlik, A.F. & J.P. Thissen, 2011. Hafted armatures and multi-component tool design at the Micoquian site of Inden-Altdorf, Germany. *Journal of Archaeological Science* 38(7), 1699–708.

Pettitt, P.B., 2011a. The living as symbols, the dead as symbols: problematising the scale and pace of hominin symbolic evolution, in *Homo symbolicus: the Dawn of Language, Imagination and Spirituality*, eds. C.S. Henshilwood & F. d'Errico. Amsterdam: John Benjamins, 141–61.

Pettitt, P.B., 2011b. Religion and ritual in the Lower and Middle Palaeolithic, in *The Oxford Handbook of the Archaeology of Ritual and Religion*, ed. T. Insoll. Oxford: Oxford University Press, 329–43.

Pierce, C., K.R. Adams & J.D. Stewart, 1998. Determining the fuel constituents of ancient hearth ash via ICP-AES analysis. *Journal of Archaeological Science* 25(6), 493–503.

Powell, A., S. Shennan & M.G. Thomas, 2009. Late Pleistocene demography and the appearance of modern human behavior. *Science* 324, 1298–301.

Purdy, B.A. & H.K. Brooks, 1971. Thermal alteration of silica minerals: an archaeological approach. *Science* 173, 322–5.

Regert, M., 2004. Investigating the history of prehistoric glues by gas chromatography-mass spectrometry. *Journal of Separation Science* 27 (3), 244–54.

Roebroeks,W., M.J. Sier, T.K. Nielsen *et al*., 2012. Use of red ochre by early Neandertals. *Proceedings of the National Academy of Sciences of the USA* 109(6), 1889–94.

Rossano, M.J., 2009. Ritual behaviour and the origins of modern cognition. *Cambridge Archaeological Journal* 19(2), 243–56.

Rots, V., 2002. Hafting Traces on Flint Tools: Possibilities and Limitations of Macro- and Microscopic Approaches. Unpublished PhD dissertation, Katholieke Universiteit Leuven.

Rots, V., P. van Peer & P.M. Vermeersch, 2011. Aspects of tool production, use, and hafting in Palaeolithic assemblages from northeast Africa. *Journal of Human Evolution* 60(5), 637–64.

Šajnerová-Dušková, A., J. Fridrich & I. Fridrichová-Sýkorová, 2009. Pitted and grinding stones from Middle Palaeolithic settlements in Bohemia: a functional study, in *Non-flint Raw Material Use in Prehistory: Old Prejudices and New Directions. Proceedings of the XV Congress of the U.I.S.P.P.*, eds. F. Sternke, L. Eigeland & L.-J. Costa. (British Archaeological Reports, International Series 1939.) Oxford: Archaeopress, 145–51.

Schenker, N.M., A.-M. Desgouttes & K. Semendeferi, 2005. Neural connectivity and cortical substrates of cognition in hominoids. *Journal of Human Evolution* 49(5), 547–69.

Schmidt, P., S. Masseb, G. Laurent *et al*., 2012. Crystallographic and structural transformations of sedimentary chalcedony in flint upon heat treatment. *Journal of Archaeological Science* 39(1), 135–44.

Schmidt, P., G. Porraz, A. Slodczyk *et al*., in press. Heat treatment in the South African Middle Stone Age: temperature induced transformations of silcrete and their technological implications. *Journal of Archaeological Science*, http://dx.doi.org/10.1016/j.jas.2012.10.016

https://doi.org/10.1017/S0959774313000309 Published online by Cambridge University Press

Schwertmann, U. & R.M. Cornell, 1991. *Iron Oxides in the Laboratory: Preparation and Characterization*. Weinheim: Wiley-VCH Press.

Settle, J.E., C.T. Dawes, N.A. Christakis & J.H. Fowler, 2010. Friendships moderate an association between a dopamine gene variant and political ideology. *The Journal of Politics* 72(4), 1189–98.

Shea, J.J., 2011. *Homo sapiens* is as *Homo sapiens* was: behavioral variability versus 'behavioral modernity' in Paleolithic archaeology. *Current Anthropology* 52(1), 1–35.

Shennan, S., 2001. Demography and cultural innovation: a model and its implications for the emergence of modern human culture. *Cambridge Archaeological Journal* 11(1), 5–16.

Sievers, C. & L. Wadley, 2008. Going underground: experimental carbonization of fruiting structures under hearths. *Journal of Archaeological Science* 35(11), 2909–17.

Texier, P.-J., G. Porraz, J. Parkington *et al*., 2010. A Howiesons Poort tradition of engraving ostrich eggshell containers dated to 60,000 years ago at Diepkloof Rock Shelter, South Africa. *Proceedings of the National Academy of Sciences of the USA* 107, 6180–85.

Tryon, C.A. & S. McBrearty, 2006. Tephrostratigraphy of the Bedded Tuff Member (Kapthurin Formation, Kenya) and the nature of archaeological change in the later middle Pleistocene. *Quaternary Research* 65(3), 492–507.

Van Peer, P., V. Rots & J.M. Vroomans, 2004. A story of colourful diggers and grinders: the Sangoan and Lupemban at site 8-B-11, Sai Island, northern Sudan. *Before Farming* 3, 1–27.

Van Peer, P., V. Rots & P.M. Vermeersch, 2008. A wasted effort at the quarry: wear analysis and interpretation of an MSA lanceolate point from Taramsa-8, Egypt. *PaleoAnthropology* 2008, 234–50.

Vanhaeren, M., F. d'Errico, C. Stringer *et al*., 2006. Middle Paleolithic shell beads in Israel and Algeria. *Science* 312, 1785–8.

Vaquero, M., S. Alonso, S. García-Catalán *et al*., 2012. Temporal nature and recycling of Upper Paleolithic artifacts: the burned tools from the Molí del Salt site (Vimbodí i Poblet, northeastern Spain). *Journal of Archaeological Science* 39(8), 2785–96.

Veth, P., N. Stern, J. McDonald, J. Balme & I. Davidson, 2011. The role of information exchange in the colonization of Sahul, in *Information and its Role in Hunter-gatherer Bands*, eds. R. Whallon, W.A. Lovis & R.K. Hitchcock. Los Angeles (CA): Cotsen Institute of Archaeology Press, 203–20.

Wadley, L., 1987. *Later Stone Age Hunters and Gatherers of the Southern Transvaal.* (British Archaeological Reports, International Series 380/ Cambridge Monographs in African Archaeology 25.) Oxford: Archaeopress.

Wadley, L., 2001. What is cultural modernity? A general view and a South African perspective from Rose Cottage Cave. *Cambridge Archaeological Journal* 11(2), 201–21.

Wadley, L., 2009. Post-depositional heating may cause over-representation of red-coloured ochre in Stone Age sites. *South African Archaeological Bulletin* 64, 166–71.

Wadley, L., 2010a. Were snares and traps used in the Middle Stone Age and does it matter? A review and a case study from Sibudu, South Africa. *Journal of Human Evolution* 58(2), 179–92.

Wadley, L., 2010b. Cemented ash as a receptacle or work surface for ochre powder production at Sibudu, South Africa, 58,000 years ago. *Journal of Archaeological Science* 37(10), 2397–406.

Wadley, L., 2010c. Compound-adhesive manufacture as a behavioral proxy for complex cognition in the Middle Stone Age. *Current Anthropology* 51(Supplement 1), S111–19.

Wadley, L., 2010d. A taphonomic study of ochre demonstrates post-depositional color transformations. *Journal of Taphonomy* 8, 243–54.

Wadley, L., 2013. Gender in the prehistory of sub-Saharan Africa, in *A Companion to Gender Prehistory*, ed. D. Bolger. New York (NY): John Wiley & Sons, 313–32.

Wadley, L., B.S. Williamson & M. Lombard, 2004. Ochre in hafting in Middle Stone Age southern Africa: a practical role. *Antiquity* 78, 661–75.

Wadley, L., T. Hodgskiss & M. Grant, 2009. Implications for complex cognition from the hafting of tools with compound adhesives in the Middle Stone Age, South Africa. *Proceedings of the National Academy of Sciences of the USA* 106, 9590–94.

Wadley, L., C. Sievers, M. Bamford, P. Goldberg, F. Berna & C. Miller, 2011. Middle Stone Age bedding construction and settlement patterns at Sibudu, South Africa. *Science* 334, 1388–91.

Watt, J.M. & M.G. Breyer-Brandwijk, 1962. *Medicinal and Poisonous Plants of Southern and Eastern Africa.* 2nd edition. Edinburgh & London: E. and S. Livingstone.

Watts, I., 1997. The Origins of Symbolic Culture: the Southern African Middle Stone Age and Khoisan Ethnography. Unpublished PhD dissertation, University of London.

Webb, J. & M. Domański, 2009. Fire and stone. *Science* 325, 820–21.

Wendt, W.E., 1976. 'Art mobilier' from the Apollo 11 Cave, south west Africa: Africa's oldest dated works of art. *South African Archaelogical Bulletin* 31, 5–11.

Wilkins, J., B.J. Schoville, K.S. Brown & M. Chazan, 2012. Evidence for early hafted hunting technology. *Science* 338, 942–6.

Wynn, T. & F.L. Coolidge, 2003. The role of working memory in the evolution of managed foraging. *Before Farming* 2003/2002(1), 1–16.

Wynn, T. & F.L. Coolidge, 2007a. Executive Functions, Working Memory, and the Evolution of the Modern Mind. Unpublished paper presented to American Association for the Advancement of Science, San Francisco, February 15–19.

Wynn, T. & F.L. Coolidge, 2007b. A Stone-Age meeting of minds. *American Scientist* 96(1), 44–51.

Wynn, T. & F.L. Coolidge, 2009. Implications of a strict standard for recognizing modern cognition in prehistory, in *Cognitive Archaeology and Human Evolution*, eds. S.A. de Beaune, F.L. Coolidge & T. Wynn. Cambridge: Cambridge University Press, 117–27.

https://doi.org/10.1017/S0959774313000309 Published online by Cambridge University Press

Wynn, T. & F.L. Coolidge, 2010. How Levallois reduction is similar to, and not similar to, playing chess, in *Stone Tools and the Evolution of Human Cognition*, eds. A. Nowell & I. Davidson. Boulder (CO): University Press of Colorado, 83–103.

Wynn, T. & F.L. Coolidge, 2011. The implications of the Working Memory Model for the evolution of modern cognition. *International Journal of Evolutionary Biology* doi:10.4061/2011/741357.

Wynn, T., F. Coolidge & M. Bright, 2009. Hohlenstein-Stadel and the evolution of human conceptual thought. *Cambridge Archaeological Journal* 19(1), 73–83.

Ybarra, O., E. Burnstein, P. Winkielman *et al*., 2008. Mental exercising through simple socializing: social interaction promotes general cognitive functioning. *Personality and Social Psychology Bulletin* 34, 248–59.

Zilhão, J., 2007. The emergence of ornaments and art: an archaeological perspective on the origins of 'behavioral modernity'. *Journal of Archaeological Research* 15, 1–54.

Zilhão, J., 2011. The emergence of language, art and symbolic thinking: a Neanderthal test of competing hypotheses, in *Homo symbolicus: the Dawn of Language, Imagination and Spirituality*, eds. C.S. Henshilwood & F. d'Errico. Amsterdam: John Benjamins, 111–31.

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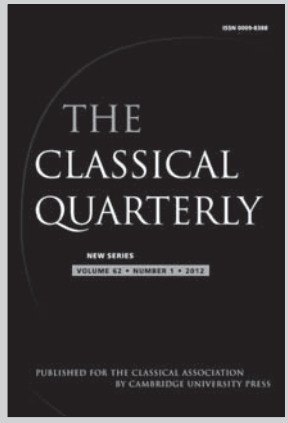
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