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Reviewed work(s):
Source: *Current Anthropology*, Vol. 51, No. S1, Working Memory: Beyond Language and Symbolism (June 2010), pp. S111-S119
Published by: The University of Chicago Press on behalf of Wenner-Gren Foundation for Anthropological Research
Stable URL: http://www.jstor.org/stable/10.1086/649836
Accessed: 03/01/2013 16:50

Compound-Adhesive Manufacture as a Behavioral Proxy for Complex Cognition in the Middle Stone Age

by Lyn Wadley

Compound adhesives were made in southern Africa at least 70,000 years ago, where they were used to attach similarly shaped stone segments to hafts. Mental rotation, a capacity implying advanced working-memory capacity, was required to place the segments in various positions to create novel weapons and tools. The compound glues used to fix the segments to shafts are made from disparate ingredients, using an irreversible process. The steps required for compound-adhesive manufacture demonstrate multitasking and the use of abstraction and recursion. As is the case in recursive language, the artisan needed to hold in mind what was previously done in order to carry out what was still needed. Cognitive fluidity enabled people to do and think several things at the same time, for example, mix glue from disparate ingredients, mentally rotate segments, talk, and maintain fire temperature. Thus, there is a case for attributing advanced mental abilities to people who lived 70,000 years ago in Africa without necessarily invoking symbolic behavior.

Introduction

What is complex cognition? The type of cognition attributed to people who think like us includes among its attributes "cognitive fluidity" (Mithen 1996), the ability to employ innovative thoughts, a capacity for novel and sustained multilevel operations (Amati and Shallice 2007), abstract thought (Barnard 2010, in this issue), and the use of recursion and concepts of past and future (Haidle 2010; Reuland 2010, both in this issue). Executive functions of the brain, which depend on frontal lobe–linked abilities, enable many of these attributes of complex cognition, and additionally, executive functions facilitate goal-directed actions, anticipation of problems, analogical reasoning, and planning over long distances or time (Coolidge and Wynn 2001, 2005; Wynn and Coolidge 2003). Examples of the type of innovative technologies implied by executive functions include alloying metals and the production of kiln-fired ceramics (Coolidge and Wynn 2006; Wynn and Coolidge 2007*a*, 2007*b*). Both are based on the ability to bring together disparate raw materials, often from distant separate sources, and to transform them, sometimes irreversibly. Combinability, also found in recursive language (Reuland 2010), occurs in the transformation of two or more metals into one.

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Innovative technologies requiring executive functions are different from technologies that use technical expertise that is normally acquired through apprenticeship (Wynn and Coolidge 2007*b*). Wynn and Coolidge caution that if expertise can produce a weapon such as a hafted spear (and it can), archaeologists should conclude that this simpler skill, rather than well-developed executive functions, was responsible. How, then, can we recognize in the deep past the presence of executive functions, abstract thought, thoughts about time, and the ability of the mind to do many things simultaneously? What behavioral proxies for these abilities would we need to recognize in the archaeological record? Long-distance and out-of-sight behavior involving response inhibition (such as setting traps) would seem to be a convincing proxy for both language and complex cognition. I shall try to convince you that other proxies exist, too. In the course of this paper, I shall analyze steps required to implement a technical strategy, in this case composite-tool manufacture using compound adhesive. I shall argue that some of the steps may have been impossible without recursion, abstraction, thoughts about past and future, and the ability to multitask. First, I examine some archaeological data.

Some Clues from Archaeological Evidence

It is unlikely that a Rubicon for the origin of complex cognition will be found archaeologically—the process of mod-

 0011-3204/2010/510S1-0012$10.00. DOI: 10.1086/649836

ernizing cognition was almost certainly gradual. Some archaeologists argue that the process began at the dawn of the Middle Stone Age (MSA) about 300,000 years ago. Ambrose (2001) proposed that composite-tool making began then (based on the appearance of backed tools at this time in Zambia) and that this new behavior reflected an increase in cognitive capacity. He hypothesized that composite-tool making requires planning and coordination of multiple, segregated tasks and that these sophisticated behaviors evolved side by side with frontal lobe development. Cognigrams that describe the steps required for the production of a wooden spear, such as those found in Germany at Schoeningen 500,000–400,000 years ago (Thieme 1997), are much simpler than those describing manufacture of composite weapons (Haidle 2010). The methods involved in making a single-component spear, such as simple stone tool knapping, could be taught to apprentices through demonstration—the "string-of-beads" approach. It could also be argued (as in Wynn and Coolidge 2007*b*) that expertise was sufficient for the construction of composite tools even though these require an enormous outlay of labor for producing armatures and for hafting stone inserts (Ambrose 2001; Torrence 2002). However, I believe that this process is far more complex than previously has been recognized. As a case study, I explore the evidence for composite weaponry in stone tool industries of the MSA of South Africa—specifically at two sites: Rose Cottage Cave and Sibudu Cave—and I then describe my replications of composite tools using compound glues.

Rose Cottage Cave, in the eastern Free State, has multiple MSA layers with ages between about 26,000 and 100,000 years ago (Jacobs et al. 2008*a*; Valladas et al. 2005; Wadley 1997). Sibudu Cave, in KwaZulu-Natal, has multiple MSA layers dating between 35,000 and about 80,000 years ago (Jacobs et al. 2008*a*, 2008*b*; Wadley 2005*a*, 2006*a*; Wadley and Jacobs 2006). In a preliminary residue and use trace analysis of a variety of MSA and Later Stone Age (LSA) stone tools from Rose Cottage Cave, Williamson (1997) detected the presence of red ochre and polish marks on the bases of many of the tools where we expect that they would have been attached to handles or shafts. This alerted us to the possibility that at least some stone tools had been hafted to handles or spear shafts using ochre as an ingredient of the adhesive. Here I examine two classes of stone tools: points and segments.

Points

Points are sufficiently common in the MSA sequence that they are often used as a defining feature of technocomplexes that lasted from about 300,000 to 25,000 years ago (McBrearty and Brooks 2000). It is widely accepted that stone points are tips of spears in both the African MSA and the European and Middle Eastern Middle Paleolithic (e.g., see Minichillo 2005; Shea 2006; Villa, Delagnes, and Wadley 2005; Villa and Lenoir 2006). Spears can be thrusting weapons or throwing weapons (Hughes 1998). Thrusting spears are handheld, while throwing spears are flight weapons (i.e., projectiles such as javelins).

Points have a variety of base shapes and thicknesses because some were deliberately thinned to fit their shafts. All points share the need to be hafted in a single direction, with the tip at the distal end of the weapon where it can penetrate the hide of prey. Use trace analyses of Sibudu points by Lombard (2005, 2006*a*; Wadley, Williamson, and Lombard 2004) revealed clusters of minute fractures on the basal laterals of points, which implies hafting. The damage was often accompanied by plant gum/resin and other plant residues, which suggests that the hafts were wooden and that plant-based adhesive was used, sometimes together with twine. A variety of adhesive types may have been employed because ochre stains were recurrently associated with the plant residues at the bases of the points (Wadley, Williamson, and Lombard 2004; Williamson 2004). The variability among glues may imply different functions for the spearheads; for example, handheld thrusting spears need unyielding glue to allow repeated thrusts. In contrast, projected spears, such as javelins, might have been designed so that the stone tip would break within the body of the prey. This could be achieved by using brittle glue that would shatter on impact. I shall discuss glue types in more detail later. Animal product residues are concentrated on the distal ends of many of the points that Lombard (2005) analyzed, confirming that they were used as hunting weapons.

While stone-tipped spears are composite weapons because they have minimally two components—shaft and stone tip—they are not as complex as composite tools with barbs or tools with inserts that can be hafted in different directions. I now discuss a class of tools for which directionality is not constrained.

Segments

Segments (sometimes called "crescents" or "lunates") are defined as a portion of a circle with a curved, abruptly blunted back and a straight, sharp chord (Deacon 1984). Each end of a segment is pointed. The abrupt blunting (which is faceted in a manner that archaeologists call backed retouch) on the convex edge of segments probably assists their hafting by creating an area of friction for the firm attachment of adhesives (Lombard 2007; Nuzhnyi 2000; Phillipson 1976).

Segments make only punctuated appearances in the MSA and LSA. They have been found in the earliest Central African MSA, with an age of about 300,000 years (Barham 2002), but they are thereafter rare until much later. In southern Africa, between about 70,000 and 55,000 years ago, segments and other backed tools were the most common stone tools in an MSA industry called the Howiesons Poort. Segments from the MSA and the mid-Holocene LSA seem to have had multiple uses, including cutting (J. Deacon 1995; Wadley and Binneman 1995), and the long cutting edges of some segments make them ideal for use as knives. Large MSA segments may

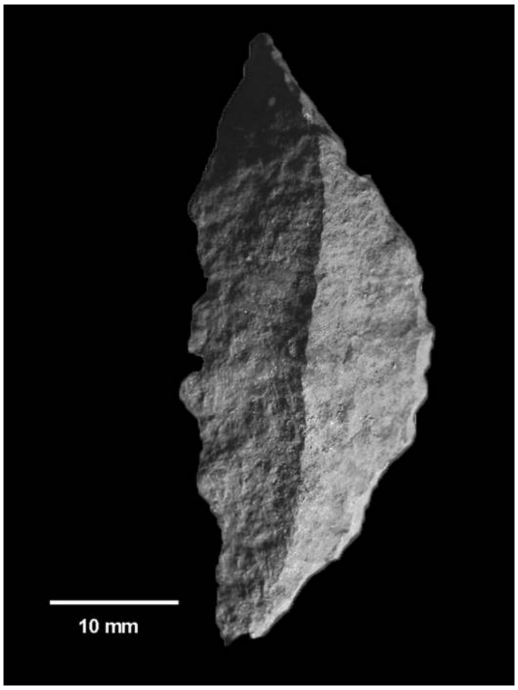

Figure 1. Dolerite segment from Sibudu showing ochre stain on its curved back.

sometimes have been used as barbs on spears or as spearheads themselves, while their small LSA counterparts may have been used as tips of arrowheads (H. J. Deacon 1995). McBrearty and Brooks (2000) and Ambrose (2001) suggest that MSA segments entail the presence of composite projectiles, although not necessarily the earliest forms of these weapons (Brooks et al. 2006). Ethnographic collections and composite weapons recovered from ancient sites show that segments and even small blades or flakes were weapon components in the past (Binneman 1994; Clark 1975; Clark, Phillips, and Staley 1974).

Residue analysis supports the suggestion that backed edges were designed to facilitate hafting because plant gum/resin, sometimes mixed with ochre or other substances, was found on the backed edges of segments and other backed tools from the Howiesons Poort industry at Rose Cottage (Gibson, Wadley, and Williamson 2004) and Sibudu (Delagnes et al. 2006; Lombard 2006*b*, 2007, 2008; fig. 1). Segments, because of their shape, with the straight cutting edge along the full length of the tool, cannot be bound with twine (the cutting edge would sever the twine), and the hafting of these stone inserts must have depended entirely on robust adhesives.

Ochre-stained segments were also found in Kenya at Enkapune Ya Muto, dated to between 50,000 and 40,000 years ago (Ambrose 1998). At Sibudu, in layers with ages somewhere between 70,000 and 61,000 years ago, Lombard (2006*b*, 2007, 2008) discovered that animal products were concentrated on the sharp, straight cutting edges of the segments, implying that these were the working ends of the tools. Use trace analyses demonstrate that haft material was either bone or wood; furthermore, carefully mapped positions of glue residues show that segments could have been hafted in a variety of positions (Lombard 2007, 2008). By rotating a segment so that its cutting edge faces different directions, it can be hafted to form one of a variety of tools, weapons, or weapon components such as barbs. It can be hafted vertically into a lateral slot on a handle to form a knife blade. Several such insertions can form a composite sicklelike knife. Through rotation, segments can be hafted to form at least four different types of hunting weapon: (1) transverse arrowheads (with the broad cutting edges placed horizontally), (2) arrowheads or spearheads with pointed tips and asymmetrical basal barbs (with the segments placed diagonally at about 60°), (3) split-point arrowheads or spearheads (by placing two segments back-to-back), and (4) long, thin arrowheads (by placing segments vertically; fig. 2).

Replicated segments used experimentally as projectile weapons (on a carcass, not a live animal) by Pargeter (2007) demonstrated that all four of these segment rotations create satisfactory weapon tips. Transverse arrowheads were recovered in their entirety in ancient Egyptian sites (Clark 1975). The elongated shape of a segment, with the sharp cutting edge on its longest axis, suggests that it cannot be bound to its

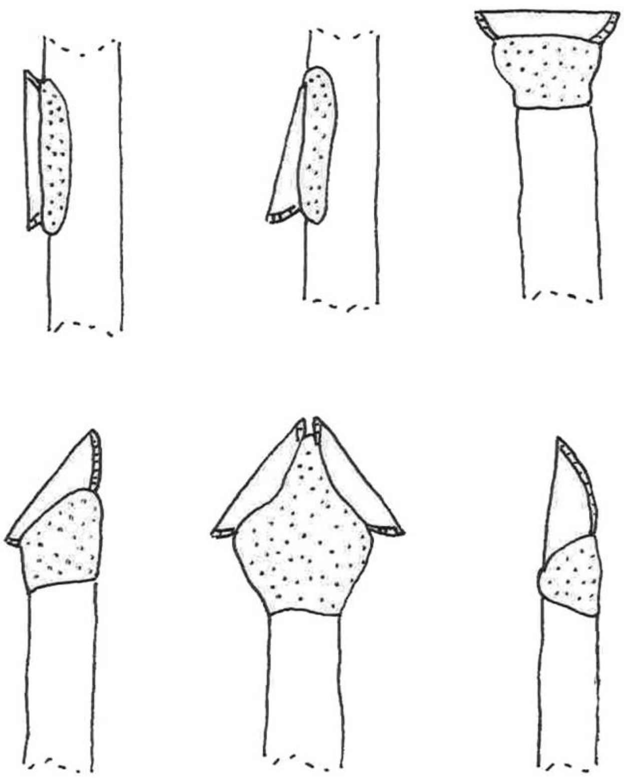

Figure 2. Six ways in which segments can be rotated for use as tools and weapons. The stippled areas represent adhesive.

shaft with twine; instead, the segment must rely on glue for its attachment. Several adhesive recipes were used on segments at Sibudu and other sites (Lombard 2007, 2008). Dolerite and hornfels segments have high proportions of ochre stains on their backed edges, suggesting that ochre was part of the plant-gum adhesive, but fat has also been observed in the mixture. In contrast, crystal-quartz-backed tools examined by Lombard seem to have been attached to their hafts using only plant gum; few of these tools have ochre on their backing (Delagnes et al. 2006:42). Of the quartz MSA segments from Umhlatuzana, another KwaZulu-Natal MSA site, 68% have plant resin adhesives but no ochre (Lombard 2007). The use of simple gum glue without additives has advantages as well as disadvantages; it is brittle and does not resist high-impact pressure (Rots 2002:57–59) and therefore allows arrow barbs or tips to become dislodged in animal carcasses, causing fatal hemorrhages (Crombé et al. 2001:260). This effect is not desirable when handheld stabbing weapons are used; here the spear's stone insert needs to remain firmly in its haft so that the hunter can, if necessary, make repeated thrusts at prey.

The results of a metric study of Sibudu segments (Wadley and Mohapi 2008) support those from use trace analyses and experimental "hunting": there are at least three separate populations of segments based on their production from quartz, hornfels, and dolerite. Attributes such as the length and breadth of segments are markedly different between the rock-type populations: quartz segments are significantly shorter, narrower, and thinner than hornfels segments, which are in turn shorter, narrower, and thinner than dolerite segments. The morphological study of Sibudu MSA segments (Wadley and Mohapi 2008) shows that the toolmakers appreciated the properties of rocks—their flaking, wear, and impact possibilities—and that they selected certain size ranges and size ratios of segments for discrete weapons.

This evidence for variable use of segments shows that they are not a single tool type other than in archaeological classification systems. The ancient artisans chose specific configurations of rocks, segment sizes, adhesives, and hafting strategies while holding in mind the desired end product. Then, through differential rotation of the segments, they were able to create an assortment of weapons and tools. Rots (2002) claims that the flexible angle at which a tool can be placed is the main advantage to hafting with adhesive. The rotation of segments was therefore made possible through the production of effective glues that did not require additional support from twine bindings around the tool.

Historical records suggest that ochre was still recently used as a loading agent for adhesives in Australia, where aborigines combine vegetal fiber and ochreous dust and sand with their resins (Rots 2002:60). Bushmen from Namaqualand, South Africa, used "euphorbid milk and red clay" as "cement" for attaching feathers to arrows, according to Doctor Atherstone, who made the observation in 1854 (Webley 1994:61). The red clay may have been ochre.

Prehistoric adhesive recipes probably varied according to the needs of tools or weapons (Wadley 2005*b*, 2006*b*), and robust compound adhesives may not always have been desirable, even for attaching segments to their hafts. Simple plant gum creates a brittle adhesive that tends to shatter on impact. As we have seen, this is not a disadvantage when stone inserts are intended to break within the body of the prey, and some nineteenth-century South African quartz arrowheads were intended to do precisely this (Clark 1975). Plant gum may also have been preferred for attaching the tiny MSA quartz segments from Sibudu to their hafts if they were arrowheads.

Red ochre was not the only suitable loading agent for compound adhesives, and it was sometimes replaced with other ingredients such as sand. Although MSA adhesives often have ochre in them, LSA adhesives do not (Binneman 1983; Binneman and Deacon 1986; Deacon 1979; Deacon and Deacon 1980; Jerardino 2001; Mitchell 1995; Phillipson 1976; Schweitzer 1979). I now describe my replication studies with stone tools, hafts, and adhesives in an attempt to explain the complexity of decision making that seems to have been associated with the hafting of tools, particularly segments, in the MSA. The descriptions are detailed so that the reader can evaluate the cognitive requirements of the process.

Experimental Hafting of Hunting Weapons

My experiments involved mounting stone tools on wooden handles using natural adhesives, all of which had plant gum from *Acacia karroo* as their base (Wadley 2005*b*; Wadley, Hodgskiss, and Grant 2009). Simple adhesive comprised *Acacia* gum alone; compound adhesives combined *Acacia* gum with powdered ochre and sometimes a small amount of beeswax.

Collection of Ingredients

Replicated hafting of tools involves the collection of (1) straight sticks of a wood type suitable for handles or shafts (I used *Grewia flava*, from which Kalahari Bushmen make bows and other wooden tools, and I selected straight branches of similar thickness); (2) firewood suitable for a fire that will burn with sustained medium heat; (3) rocks for making flakes; (4) a hammer stone for knapping the flakes; (5) hematite (Fe_2O_3) nodules for producing ochre powder; (6) coarse-grained flat rocks for grinding the ochre; (7) gum from *A. karroo* trees; and (8) *Hypoxis rigidula* leaves for twine (although twine was used on only a few tools). The collecting process from a variety of disparate sources was time consuming and involved considerable planning.

Initial Processing of Ingredients

The initial processing of the ingredients was as follows: (1) Stone flakes were knapped, first for cutting the wooden shafts and second for making suitable sharp inserts for the weapons.

(2) Sticks were shaped to produce shafts. L-shaped platforms worked best for securely holding my stone tools, although other experiments used split shafts so that the stone could be inserted into it. The L-shaped platforms were carefully whittled to maintain right angles, and the shaft laterals were straightened and trimmed to remove nodules. The shafts were cut from wet wood. These were dried for a week so that sap would not moisten the adhesive and the shaft would not shrink after the weapon's creation. (3) Hematite nodules were ground by rubbing them on coarse stone slabs to produce powdered ochre. This is a lengthy process; about 10 mL of powder is produced per hour of grinding. About 50 mL of powder is needed for adhesive for 10 tools. Several coarse slabs are needed for the task because the grinding process is slower when the slab surface becomes smooth. Using a coarse slab is essential because tiny, angular quartz particles (80–1,000 μm) rub off the slab and become incorporated into the fine ochre powder. This coarse aggregate provides a variety of surface area sizes within the adhesive, and this is necessary for successful bonding, just as a variety of particle sizes creates successful concrete.

Once the ochre powder, shaped handles, and flakes were ready, the fire was lit, and the composite tool production started. I first describe the hafting of tools with *Acacia* gum.

Simple Adhesives Made from Plant Gum

Acacia gum is nature's own adhesive, and its role is to seal a tree's wounds. In several replications, gum was used alone (Wadley 2005*b*). Some of the gums were heated, and others were allowed to dry naturally. The consistency of the gum is variable; drier gums are easier to work with than runny ones, which are very sticky. Gum that is fairly dry can be molded around a tool and air-dried with no further processing. Wet gum is difficult to control, and it needs to be dehydrated over a fire to prevent it from dripping off the haft, which would cause the stone tool to fall from its haft.

Gum dries slowly, even next to a fire, and the end product is brittle, full of cracks and air bubbles, and sometimes crumbly. Like glass, gum adhesive tends to shatter on impact. *Acacia* gum is water soluble and hydroscopic; consequently, damp conditions will cause this simple adhesive to become tacky, allowing the stone tool to fall from its haft.

Compound Adhesives Made with Plant Gum, Ochre, and Coarse Aggregate

These adhesives were mixed by adding powdered ochre to *Acacia* gum (for detailed experimental results, see Wadley 2005*b*; Wadley, Hodgskiss, and Grant 2009). Sticky gum needs more ochre than dry gum to make it workable. When the mixture is workable, it can be easily molded to a tool. There is no recipe that can be followed; making these glues is not like baking a cake. The technique is not routine; it entails evaluating the qualities of the ingredients and adjusting their quantities accordingly. It requires complete, undivided attention. A tiny piece of beeswax was added to a few of the adhesives, and this creates satisfying plasticity in the compound. However, a dab too much of beeswax results in an adhesive with "creep"; once dry, it shrinks and releases the stone tool from the haft.

By adding an aggregate, the artisan cuts back on the time that is required to dehydrate and harden the adhesive. Moderate heat from a fire dries and hardens the adhesive considerably faster than drying without heat. Air-dried adhesive takes a long time to set—24 hours after manufacture, a stone tool will dislodge from its haft immediately if it is used, revealing wet adhesive as a soft center inside the hardened outer crust. My experiments showed that it takes as long as 6 days for air-dried adhesive to dry and harden properly. However, tools that were slowly dried near a fire for between 3 and 4 hours (rotating them about every 10 minutes) could be used immediately without them breaking. The use of fire for dehydrating the ochre-loaded adhesive is an art, and the tools' distance from the fire must be judged carefully. On one of my first incompetent attempts at heating a newly hafted tool over the fire, the adhesive swelled and the outer crust became hard and charred, leaving an air-filled hollow under the crust. This weakened the adhesive and the stone tool fell out. When tools are heated too rapidly, the adhesive begins to boil, and this also creates cracks and weakness. Vigilance, keen judgment, and an understanding of the feel and appearance of the end product are required; failure can befall the tool at any stage of its gestation if the artisan's attention wavers.

Ochre-loaded adhesive is not water soluble or hydroscopic after it has been properly dried. A combination of gum and ochre provides an adhesive that cannot be reheated for recycling, and the components cannot be separated after they have been mixed and dried. The process is irreversible.

One clue to the success of ochre as a loading agent may be in nature: iron oxide minerals act as cementing agents in some sedimentary rocks, such as banded ironstone or conglomerates; the iron oxide is chemically deposited from solutions containing the mineral. A change in pH is part of this geological process, and after ochre is added to gum, a change in pH also takes place (Wadley, Hodgskiss, and Grant 2009). Pure synthetic hematite powder was never successful for adhesive manufacture because it lacks coarse grains. What makes concrete set successfully in a modern engineering context is the amalgamation of sand with fine and coarse stone aggregate to bind the fine, powdery particles of cement when water is added. Clearly, a similar combination of ingredients is required to create adhesive with ochre powder and gum. By grinding ochre nodules directly on coarse sandstone slabs, as I did (and similar ones have been found at Sibudu Cave), the ancient glue makers would have automatically created a coarse component in their glues. If this method was not used, sand would need to be added to make up the necessary coarse-grained aggregate.

Are Compound Adhesives Proxies for Complex Cognition?

My adhesive replications and metric studies and the use trace analyses conducted by Lombard (2006*a*, 2006*b*, 2007), Williamson (2004), and Gibson, Wadley, and Williamson (2004) imply that artisans in the MSA had considerable technical skill. However, Early Stone Age artisans also had enviable skill (Wynn 1979, 1989), but this does not suggest that they had complex cognition. The link between technological sophistication and cognitive complexity needs to be demonstrated, not assumed. We need to show what types of mental architecture are indispensable for specific innovations.

Was it serendipitous that people 70,000 years ago got the intricate process right when they were making compound adhesives? I tend to think that it was not. Sticky *Acacia* gum, nature's own adhesive, can be used intuitively by people. However, when this simple glue became inadequate, people did not seek a more potent natural adhesive. Instead, they "renovated" their existing plant-based glue in an innovative and nonintuitive manner. In order to create compound glue with plant gum as its base, they selected a product—ochre powder—that has no gluelike attributes. Fat and wax also lack attributes of natural adhesives, and these products were sometimes mixed with gum and ochre. It could not be predicted, without considerable imagination, that the use of items with nonadhesive properties could create successful glue. We can express the transformation process, which involves a chemical reaction: loose, dry powder + sticky, wet gum + heat = hard, dry concreted adhesive. The whole is indeed greater than the sum of its parts; the whole is a marriage of the most desirable attributes of each separate ingredient. The concept of transformation is important to the production of the irreversible adhesive, and I argue that the type of thought process required to make compound adhesives is not much different from that required for technologies such as alloying metals and firing ceramics.

In some ways, the creation of compound glues mimics the combinability that characterizes modern language (Reuland 2010). Embedded recursion—necessary for linguistic dependencies—requires that material stay internally represented before and after it is realized (ab, aabb, aaabbb, . . . a^nb^n). It enables the emergence of infinite combinability, but the system must hold in mind what it has previously done in order to carry out what still has to be done. Haidle (2010) claims that human manipulation of objects sometimes shows structural and cognitive parallels to language, including the use of recursion and concepts of past and future. The parallel can certainly be drawn with respect to the manufacture of compound adhesives, where there is constant feedback, reassessment, and correction of problems throughout all the stages of action. The process also involves coordinating past and future actions to ensure a successful end product. Thoughts about time—past and future—are important in modern language, as is abstraction (the ability to recognize regularities in diversity; Reuland 2010). Among its many roles, language enables people to talk about behavioral variation, which can be abstracted, enabling innovation from the circuit.

The artisans who made compound adhesives must have understood and abstracted the individual attributes of ingredients such as plant gum and ochre, as well as the combined properties of these inorganic and organic materials. Thus, qualities such as wet, sticky, and viscous were mentally abstracted, and these meanings were counterpoised against the properties of dry, loose, and dehydrating. The second set of attributes opposes the first, but it is also remedial to it so that, in combination, the attributes are complementary. I argue that this provides an example of fourth-order abstraction as described by Barnard (2010), who makes the point that simultaneous mental processing of two levels of meaning would not have been possible before modern complex cognition. Fourth-order abstractions are schematic models of self, others, and world, and their content can be compared with generic feelings or intuition (Barnard 2010). Only the most advanced mental architecture can control walking, talking, and thinking at the same time, and this mental architecture adds the ability to reorder elements of ideas and to evaluate whether an idea is worth thinking about (Barnard 2010).

It is difficult to imagine how the expert glue maker could train an apprentice to make compound adhesives without explaining, in abstract terms, attributes and conditions such as stickiness, viscosity, workability, consistence, plasticity, texture, particle size, temperature, concretization, water solubility, hydroscopic, dehydration, reversible process, irreversible process, shrinkage, homogeneity, creep, and shrinkage. The concept of the irreversible transformation had to be explained using language as we understand it, for example, incorporating recursion, abstraction, and words to describe both the past and the future.

Executive functions—such as projecting future action, anticipating problems, and preparing responses—are implicated in the making of compound, heat-treated glues. The master glue maker would have needed to hold in mind a template for the end product because adhesive manufacture is not an exact science and there is no set recipe for success. Quantities of ingredients must be varied according to the condition of each at the time of use. Viscosity of plant gum and the texture and grain size of ochre powder must be gauged while the adhesive is being mixed in order to get the right consistency. The moisture content of gum varies from tree to tree and season to season. Ochre nodules produce powder of different grades depending on how and where the parent rock weathered. The ancient artisans also needed to understand the effects of varying temperature on their adhesives and, in turn, the temperature potentials of dissimilar woods. The process thus provides an example of Amati and Shallice's (2007) nonroutine thought that aims for novel goals.

Thought experiments require holding a multiplicity of information in the mind at the same time. Not only did the makers of the MSA composite tools hold in mind the vagaries of compound-adhesive manufacture; they also simultaneously had to think about the correct position for placing stone inserts on the hafts. By about 70,000 years ago, artisans were able to perform mental rotation of segments in order to create implements of different shapes with different objectives. The artisans needed to think abstractly about the qualities of their segments in order to visualize their use after rotation. More important, successful mental rotation seems to require advanced working-memory capacity and, in turn, complex cognition. The connection has been made by psychologists using complex span tasks that are reliable and valid psychometric tests for measuring working-memory capacity. The tasks are able to predict performance in cognitive assignments such as listening comprehension, language comprehension, following oral and spatial directions, reasoning, and hypothesis generation (Engle 2010, in this issue). Among complex span tasks used by psychologists are, for example, spatial ones requiring a person to rotate a letter mentally or decide whether a figure is symmetrical around a vertical axis (Engle 2010; Kane et al. 2004). Performance on such spatial tasks is linked to higher-order cognitive capabilities such as executive function and complex reasoning (Kane et al. 2004).

In conclusion, I maintain that compound-adhesive manufacture in southern Africa 70,000 years ago (and possibly earlier, but this has not yet been explored) required complex cognition. As is the case in recursive language, the artisan needed to hold in mind what was previously done in order to carry out what was still needed. People were able simultaneously to talk, think, mix glue, maintain fire temperature, and mentally rotate stone tools. As I have shown, some of the steps in the making of compound adhesives and composite tools are not possible without abstraction, recursion, and cognitive fluidity. Consequently, there seems to be a strong case for attributing advanced mental abilities to people who lived 70,000 years ago in Africa (and perhaps elsewhere if similar processes are discovered out of Africa).

It is not yet possible to attribute complex cognition to people who lived 300,000 years ago. In the Zambian site of that age, Twin Rivers, quantities of coloring materials occurred with backed tools, which Barham (2002) believes may be the earliest of their kind and may be indicative of composite tools (Ambrose 2001). It would be truly remarkable if these backed tools were hafted with compound adhesives to form many types of weapons, but there is, as yet, no evidence for this, and the backed tools may have been handheld. D'Errico's (2008; d'Errico and Soressi 2002) work at Pech de l'Azé, France, has demonstrated that there was systematic pigment use by Neanderthals, so the use of pigment itself is not species specific. Neanderthals also made use of pitch for attaching their stone tools to hafts (Boëda et al. 1996). The ingenious Neanderthal technology involved the use of controlled heat because the resin portions of birch tar do not melt below 340°C and they burn above 400°C (Koller, Baumer, and Dietrich 2001). What seems to distinguish the compound adhesives discussed here from the birch tar used by Neanderthals is the multitasking evident in the manufacture of the *Acacia* gum and ochre compound glues. However, archaeological data are added to almost daily, and we may yet be in for surprises regarding the technological and cognitive abilities of hominids before the period under review. I suggest, however, that if other compound glues are discovered archaeologically, they should be experimentally reproduced. It is only through this kind of work that we can gain an understanding of the mental processes involved in technology.

My case study from southern Africa suggests that archaeologists working with sites from different periods and in different parts of the globe may also find it useful to analyze the mental processes implied by technologies evident at their sites. Because few archaeologists have agreed on an appropriate definition of symbolic behavior in the deep past, the type of method I offer here seems to provide a useful alternative for recognizing complex cognition.

Acknowledgments

I am deeply indebted to Tom Wynn, Fred Coolidge, and Wenner-Gren for giving me the opportunity to share stimulating experiences and discussions at the Working Memory Symposium. Moreover, I am grateful to Tom and Fred for the intellectual challenge that their seminal research has provided. I appreciate the constructive comments made by reviewers of this paper. The research described here has been funded by the National Research Foundation, which does not necessarily share the views expressed here. I thank the Institute of Human Evolution and the School of Geography, Archaeology and Environmental Studies for their ongoing support.

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