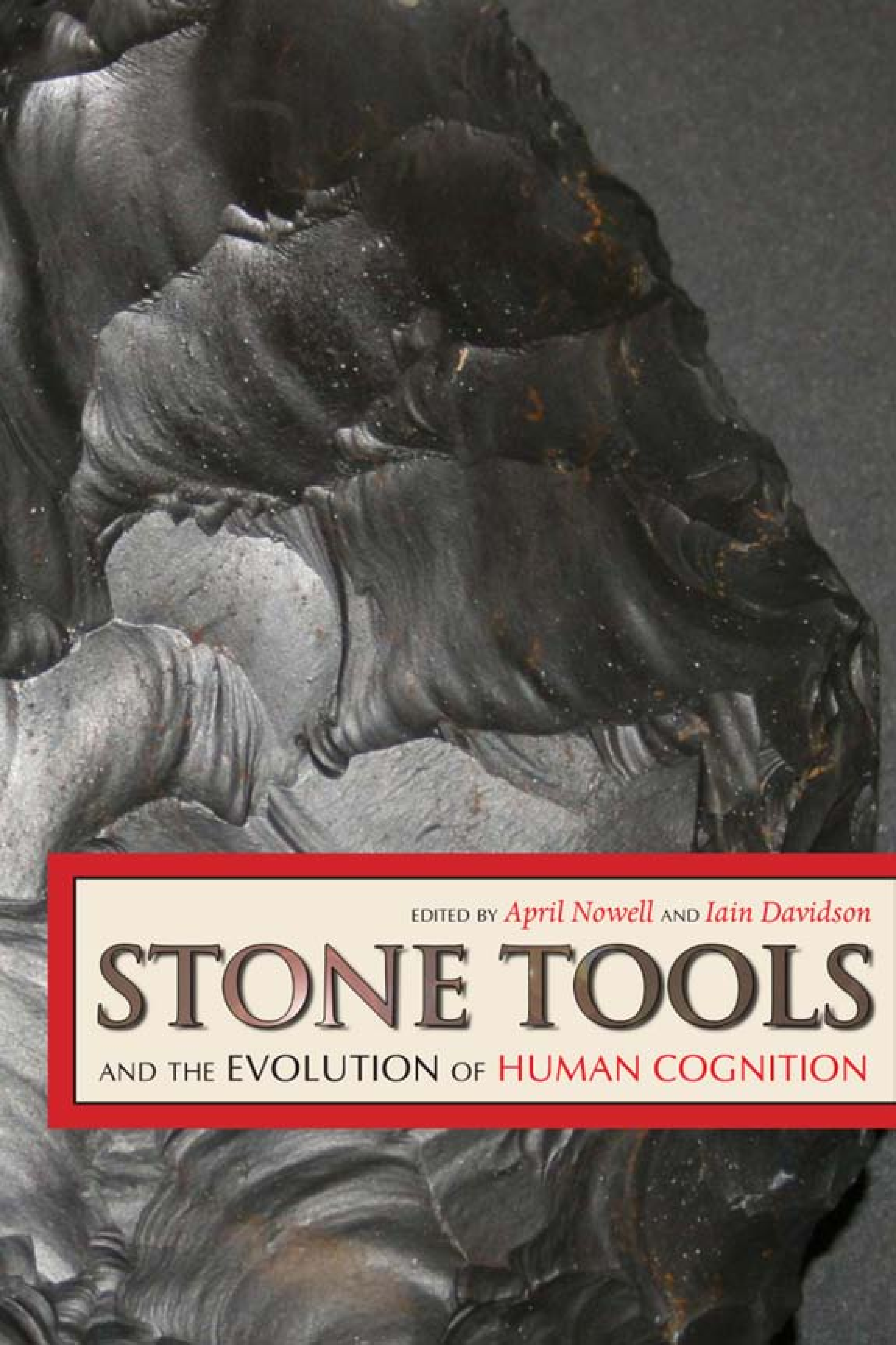

EDITED BY *April Nowell* AND *Iain Davidson*

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AND THE EVOLUTION OF HUMAN COGNITION

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For Jon (AN) and Helen (ID)

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STONE TOOLS

AND THE EVOLUTION OF HUMAN COGNITION

ONE

Introduction and Overview

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Stone tools are among the most distinctive features of the lives and evolution of hominins and, through them, material culture came to play an increasingly important role in the behavior of our ancestors. As a result, material culture and stone tools in particular have given archaeologists a window onto behaviors and lifeways that have long since disappeared. Although stone tools were initially studied primarily as indicators of cultural achievements and then of technology and subsistence strategies, our understanding of the kinds of information that can be inferred from stone tools has expanded significantly in recent years. This broadening of analysis is linked to the development of cognitive archaeology. In this volume, we focus on the multiple ways in which stone tools can inform archaeologists about the evolution of hominin cognitive abilities.

THE EARLIEST STONE TOOLS

In the 1960s Mary and Louis Leakey uncovered 1.8 million-year-old stone tools at the site of Olduvai Gorge in Tanzania. These tools, which archaeologists called the Oldowan industry, were later associated with *Homo habilis*, the first member of the genus *Homo*. This was a significant discovery because relative to older hominin species that were not thought to be tool users, *H. habilis* had a larger brain size and possessed anatomical features reminiscent of later species (e.g., reduced molar size, flatter face). Increasing cranial capacity, tool use, and more modern-looking features fit together in the story of what made humans unique. In fact, for the first time the use of material culture was included in the official definition of a species (Leakey, Tobias, and Napier 1964)—and thus the phrase "Man the Tool Maker" was coined (Oakley 1952).

Since that time, our knowledge of the relationship between stone tools and the evolving human brain has grown and the resulting picture is predictably more complex. The earliest known stone tools now date to approximately 2.7 to 2.5 million years ago (mya) (Semaw 2000) whereas hominin evolution can be traced back using the fossil record to between 7.0 and 6.0 mya (see Wood 2002). Researchers question whether the "sudden" appearance of the Oldowan is the result of a dramatic change in cognitive abilities or the transition to a more archaeologically visible medium. One way to think about this is to consider the niche that was opened by the use of stone tools. Davidson and McGrew (2005; see also Davidson, Chapter 9) have suggested that the permanence of stone tools and the products of knapping on the landscape made a distinctive difference to the pattern of cognitive evolution. It also seems likely that *H. habilis* was not the only stone tool maker and user. Depending on how many species one recognizes between 2.5 and 1.5 mya, up to as many as eight hominin species have been found in direct or indirect association with stone tools (Toth and Schick, 2005). In addition, there is now good evidence that early hominins were using bone tools (Backwell and d'Errico 2001, 2008).

Thus, it is clear that tool use was a important behavioral adaptation of our hominin ancestors—but not only of our hominin ancestors, as there is considerable evidence that nonhuman primates also use a wide variety of tools for subsistence and display purposes (see, e.g., Boesch and Boesch 1984; Boesch et al. 1994; Goodall 1964; Whiten et al. 1999) (there is an extensive discussion of ape tools by de la Torre in Chapter 3), and that they reuse stone hammers from one year to the next, apparently remembering where they left hammers the previous season (Boesch and Boesch 1984). The key question is what are the similarities and differences in cognition that underlie human and nonhuman primate tool behavior? The search for answers to this question has led to new research directions, including teaching nonhuman primates how to knap stone (Schick et al. 1999; Toth et al. 1993); studies of the cognitive aspects of nonhuman primate tool use in the wild (Byrne 2005); archaeological excavations of nonhuman primate "sites" to see what behaviors leave archaeologically visible residue

(Carvalho et al. 2008; Mercader et al. 2007; Mercader, Panger, and Boesch 2003); PET scans of humans knapping (Stout, Chapter 8; Stout et al. 2000, 2008; Stout and Chaminade 2007); and research into the kinds of learning, memory, and skill required to make Oldowan tools versus nonhuman primate tools (see, e.g., Davidson and McGrew 2005; Haidle 2009; Wynn and McGrew 1989). This last set of studies includes questions concerning the origins of language—can you learn how to make stone tools in the absence of language (see discussion in Nowell 2000; Wynn and Coolidge, Chapter 5) or other verbal instruction (Davidson 2009)? Can you tell from flakes whether knappers were preferentially right-handed and does this imply brain lateralization and preconditions for language specialization in the left hemisphere (Corballis 2003; Noble and Davidson 1996; Pobiner 1999; Steele and Uomini 2005; Toth 1985a; Wilkins and Wakefield 1995)? Moore (Chapter 2), de la Torre (Chapter 3), and Davidson (Chapter 9) all explicitly address the question of the transition to hominin knapping from a common ancestor similar to chimpanzees and bonobos in its abilities. Davidson (Chapter 9; Davidson and McGrew 2005), in particular, draws attention to the obvious fact that apes have never been claimed to cut anything in the wild, although they can learn to cut a string in the lab. He argues that "cutting" is one of the key innovations to making stone tools part of the hominin adaptation.

STONE TOOLS IN DAILY LIFE

Based on microwear studies, experimental work, and cutmarks on animal bones, we know that our ancestors used stone tools for a variety of tasks, including skinning, disarticulating and defleshing animals, breaking open long bones to access marrow, working wood, and processing vegetable matter (see, e.g., Bunn 1981; Dominguez-Rodrigo et al. 2005; Keeley and Toth 1981; Pobiner et al. 2008; see also Shea 2007). They even used bone tools to break into termite mounds to exploit a readily available resource rich in protein (Backwell and d'Errico 2001, 2008). We know that they carried stones around the landscape because we find artifacts far from their sources (Ambrose 1998; Braun et al. 2008 and references therein; Whallon 1989), knapped stones from different sites that can be fitted back together but with some of the flakes missing (Delagnes and Roche 2005; Van Peer 1992), and cut bones with no stone tools associated with them. These observations have led researchers to study a number of cognition-based questions, including what types of mental maps are required to coordinate resources across a diverse landscape and whether this exceeds what nonhuman primates are capable of (e.g., Boesch and Boesch 1984) and the degree to which Oldowan and especially later stone industries are evidence of forethought, planning, and enhanced working memory (Haidle 2009; Wynn and Coolidge, Chapter 5). One of the ways in which scholars have attempted to show the depth of intentionality in stone tool making has been through the identification of standardized tools (see discussion in Nowell 2000; Nowell et al. 2003). Kuhn (Chapter 6) shows that even this is not straightforward and that some of the attempts need to take into account the way in which archaeological analysis forces the appearance of standardization.

Stone tools were obviously important in the everyday activities of our ancestors, but we may never know how they learned to make them in communities of their fellow creatures. It is one of the missing parts of the story. Even recent ethnographic accounts (e.g., Stout 2002, 2005) cannot claim to be complete, such is the penetration of modern technology into all societies. Yet Nowell and White in Chapter 4 show that such considerations of life histories of our hominin ancestors might be the key to understanding some of the repetitive patterning in early stone tools. They argue that some of the stasis visible in the archaeological record may be the result of demographic and not necessarily cognitive factors (see also Powell, Shennan, and Thomas 2009; Shennan 2001). They also explore how the insertion of a uniquely human childhood stage of growth and development into the typical primate pattern affects learning and sociality.

STONE TOOLS, DECISION MAKING, AND THE CONCEPTUAL PROCESS

From the moment of discovery of a handaxe in 1797 (Frere 1800), much of our understanding of our Pleistocene ancestors has been based on knowing the history of stone tool making from the earliest times until the emergence of settled agricultural societies. By the beginning of the twentieth century, the basic sequence of stone industries was well-established, at least in Western Europe (e.g., Grayson 1983). The details of the industries are now much better known (Delagnes and Roche 2005; Leakey 1971; Toth 1985b) but the basic framework has remained remarkably little changed in the intervening century (see also the discussion in Davidson and Noble 1993). As this framework emerged, it was based on the form of the distinctive artifacts, in other words, their typology: Oldowan choppers and chopping tools; Acheulian handaxes and cleavers; Levallois prepared cores and flakes; Mousterian scrapers; Upper Paleolithic blade-based end scrapers, burins, and projectile points—what Davidson (2009) has called the "OALMUP" sequence. Some of the assumptions about the wider significance of the characteristics of the European Upper Paleolithic industries have been questioned (Bar-Yosef and Kuhn 1999; Davidson 2003a; McBrearty and Brooks 2000). Wurz (Chapter 7) directly addresses some of these questions in relation to the Middle Stone Age industries of southern Africa. The contributions by both Kuhn and Wurz bring into relief just how difficult it is for analysts to separate out those components of stone tools that may indicate style or convention, from which symbolic representation of the target tool types could be inferred. This may be one of the key issues in the use of artifact form to understand cognition (see Davidson 2003b).

Cognitive approaches have affected how we approach typological studies. Typology of artifact form remained the basis for analysis for many archaeologists throughout the past century (cf. Ambrose 2001), particularly as a result of the assumption that stone artifacts should be considered as cultural products; although the emphasis switched from typologically idiosyncratic markers to a statistical analysis of relative frequencies of a range of types (see discussion in Davidson 1991). But more recently, there has been a shift away from emphasizing the artifact as an end product (Davidson and Noble 1993; Dibble 1989; Dibble and McPherron 2006; Frison 1968), appropriately in light of the paradox recognized by Hiscock and Attenbrow (2005). They ask, "[H]ow can implements be designed for, and be efficient in, a specific use if their morphology is continuously changing?" Some progress can be made toward understanding the process that created artifact form through the analysis of reduction sequences or *chaînes opératoires* (Bar-Yosef and Van Peer 2009; Pelegrin 1993)—a method for reconstructing sequences of decisions made by ancient flint knappers. In the best of cases, refitting of flakes and cores left by the knappers allows for relatively complete analysis of the knapping procedures (Delagnes and Roche 2005). In others, experimental knapping allows identification of the products that are distinctive of particular processes (see discussion in Moore 2005)—a new version of typology, but one based firmly on an understanding of processes rather than a belief that the form of the discovered artifact type was an intended product of the manufacture. Moore (Chapter 2) develops a theoretical approach to analyzing the process of flake removal in a way that shows not only how the standard sequence works but also how the operations must have been related to each other in cognition. In doing this, he derives some of his argument from Greenfield's (1991) "grammars of action," elaborated as a way of identifying cognitive development in young children through their combinations of objects in play. But because stone knapping is subtractive, Moore's argument not only is original for the understanding of stone tool knapping but also might be adapted for further understanding of the ontogeny of cognition of modern children.

STONE TOOLS AND COGNITIVE ARCHAEOLOGY

In 1954, Christopher Hawkes published an influential paper in which he described what became known as a "ladder" of archaeological inference. Following this metaphor, as one proceeded from lower to higher rungs, there was "an ascending scale of difficulty in reconstructing a culture's technology, economics, socio-political organization, and religious beliefs" from the actual physical remains that archaeologists regularly uncovered. For Hawkes, it was ironic that what was unique about humans, what made us the most interesting, was the least knowable from the archaeological record. For many archaeologists working in the 1960s and early 1970s, the mind was largely epiphenomenal (although the early assumption that the "final" Levallois flake was somehow predetermined by the whole flaking effort anticipatory of it implied a cognitive ability among Middle Pleistocene knappers that needs to be considered here). As Lewis Binford (1965, 1972) famously wrote, archaeologists were not in the business of "paleopsychology." This attitude began to change, partly through emphasis on later prehistory where the evidence was more complete (Renfrew 1982; Renfrew and Zubrow 1994), but also for earlier prehistory as the result, almost single-handedly, of the efforts of Thomas Wynn (e.g., 1979, 1981, 1989, 2002; Wynn and Coolidge 2003, 2004, and Chapter 5). Wynn has been and continues to be a pioneer in developing cognitive archaeology in a way that Binford could never have envisioned when he coined the term "paleopyschology." Wynn's research has opened our minds to the possibilities of inference from stone tools and pushed the boundaries of what we thought was possible to learn from them. Many of the studies discussed above and the chapters in this volume are a direct result of his innovative research.

The final chapter in this volume (Chapter 10), by Barnard, considers the current state of the field by discussing recent developments in inferring cognitive capabilities from stone tools. Barnard summarizes the contributions to this volume from the perspective of a behavioral scientist attempting to make inferences about the mind from the sorts of observations and theoretical perspectives available to archaeologists. Underlying Barnard's contribution is an understanding of a more complex model of cognition and its evolution (Barnard et al. 2007) that allows the early emergence, among apes and the last common ancestor of apes and humans, of complex spatial-praxic actions in a way some earlier theorists had not acknowledged. This model also predicts that complex vocal utterances and combinations of them emerged earlier among hominins than the reflexive thought generated only from the inputs of mental activity of the agent concerned. In this way, learning to make stone tools by knapping may have been guided by vocal utterances without those utterances having all of the symbolic and reflective qualities of language (Davidson 2009).

More recent fieldwork has complicated the picture the Leakeys and Oakley developed, but their intuitions were fundamental to the modern interest in the cognitive significance of stone tools. Moreover, although the accumulation of evidence from both archaeology and primatology has blurred the distinctions between human and nonhuman primates, decades of research into the relationship between stone tools and the emerging human mind have served ultimately to highlight hominin uniqueness rather than to erode it. The studies in this volume show us just how data collection and theorizing can move us forward in understanding the evolution of hominin and human cognition through the study of stone tools now and in the future.

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TWO

“Grammars of Action” and Stone Flaking Design Space

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ABSTRACT

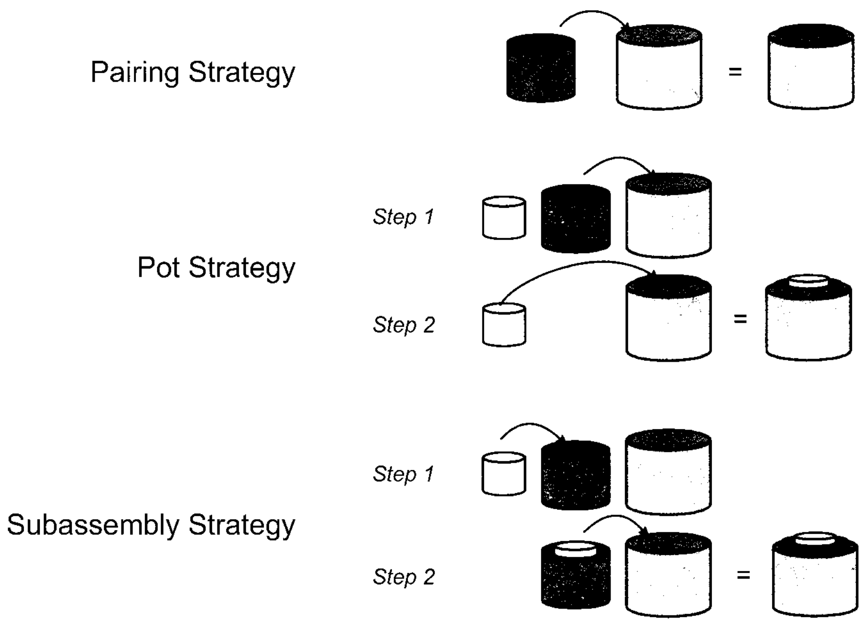
Human infants and primates use similar strategies to organize utterances and motor actions. These strategies, called “grammars of action,” are initially similar followed by an ontogenetic divergence in children that leads to a separation of complex linguistic and action grammars. Thus, more complex grammars arose after the emergence of the hominin lineage. Stone tools are by-products of action grammars that track the evolutionary history of hominin cognition, and this study develops a model of the essential motor actions of stoneworking interpretable in action grammar terms. The model shows that controlled flaking is achieved through integral sets of geometrical identifications and motor actions collectively referred to as the “flake unit.” The internal structure of the flake unit was elaborated early in technological evolution and later trends involved combining flake units in more complex ways. Application of the model to the archaeological record suggests that the most complex action grammars arose after 270 kya, although significant epistemological issues in stone artifact studies prevent a more nuanced interpretation.

INTRODUCTION

Experiments conducted by psychologist Patricia Greenfield and her colleagues explored the grammatical strategies of various primates, including monkeys, chimpanzees, bonobos, and human infants (Greenfield 1991, 1998; Greenfield and Schneider 1977; Greenfield, Nelson, and Saltzman 1972). The research demonstrated that human children consistently employ three strategies for ordering utterances and motor actions, referred to collectively as "grammars of action." Primate experiments showed that grammars of action applied by chimpanzees and children are initially similar, followed by an ontogenetic divergence by children. The authors concluded that more complex grammars of action evolved after the divergence from a common ancestor. Greenfield emphasized utterances in her research rather than motor actions "because there is no fossil record of behavior" (Greenfield 1991:545).

Greenfield interpreted these changes according to a modular model of brain function, since superseded by a more nuanced paradigm based on distributed neural networks. Nevertheless, many researchers agree with Greenfield's thesis that the evolution of higher cognitive functions, such as cognitive flexibility and syntactical ability, are linked with the evolution of motor control (Lieberman 2006). Greenfield's empirical observations remain robust because they focused on spontaneous motor behaviors (Parker 1990; Parker and Jaffe 2008:156). The enduring value of Greenfield's model for archaeologists is in the way it explicitly links cognitive evolution with motor actions. Since stone tools are physical correlates of motor actions (the ostensibly absent "fossil record of behavior"), Greenfield's model is uniquely suited for an archaeological study that tracks the part of the evolutionary story missing from Greenfield's discussion, from the common chimpanzee/hominin ancestor to modern humans. To do this, a model of the essential motor actions of stoneworking is required that can be translated into "grammars of action." Although the essential actions of stoneworking are well-understood, studies into early stone flaking have traditionally focused on tools and cores as the accumulation of those actions; a practical model suitable for applying Greenfield's model has not been forthcoming.

This study presents a model of the "design space" of knapping—the essential actions of stoneworking—in terms compatible with Greenfield's model. The goal of the study is twofold: first, to use the design space model to theoretically pinpoint some of the key turning points in technological evolution, and second, to identify those areas where our empirical evidence is vague or our epistemology weak.



2.1. Motor action strategies used to combine cups (after Conway and Christiansen 2001).

GRAMMARS OF ACTION

Greenfield's model links developmental changes in brain anatomy with changes in the hierarchical organization of speech and motor skills (Greenfield 1991). Greenfield's thesis is that changes in speech and motor skills are reflected ontogenetically in young children. This progression of abilities, when tested against living primates, has phylogenetic implications. The term "grammars of action" reflects the basic similarity between speech structure and motor skills.

Laboratory studies of human children show that there are three strategies for ordering motor actions (Greenfield 1991:532; Greenfield, Nelson, and Saltzman 1972) (Figure 2.1).

1. *Pairing strategy*. A single active object acts on a single static one to create the final structure. This involves one chain-like combination.
2. *Pot strategy*. Multiple active objects act on a single static one to create the final structure. This also involves chain-like combination but results in a longer chain.
3. *Subassembly strategy*. Multiple active objects are combined to form a subassembly, which is in turn combined with a static object or another subassembly to create the final structure. The two-level combination is hierarchical.

The three strategies are reflected in the way children organize nested cups and emerge sequentially between about eight and twenty months (Swann 1998: table 1). A similar progression is seen in the way sounds and words are combined. At about two years, the ways that children combine objects drift away from the ways that they combine sounds and words. Words are combined with increasing hierarchical complexity based on syntactical rules (Greenfield 1991:541–542). Greenfield argued that complex syntactical features have no analogues in grammars of motor action and, conversely, complex grammars of action that emerge at about the same time have no analogues in linguistic grammars (Greenfield 1991:544; see Greenfield and Schneider 1977). The increasing separation of linguistic grammars and action grammars reflects ontological changes in brain circuitry (Greenfield 1991:542–544; however, see Stout 2006:296–297).

Greenfield interpreted the grammatical competence of bonobos in light of this model (1991:545–547; Greenfield and Savage-Rumbaugh 1990) and explored how the ontological patterns of linguistic and action grammars are reflected in phylogeny (Conway and Christiansen 2001; Johnson-Pynn et al. 1999). Greenfield's premise was that brain features in different primates are homologous. Analogous brain features may be responsible for convergent pairing/pot/subassembly motor strategies seen in nonprimate species, such as parrots, but they offer little direct insight into primate evolution (Piñon and Greenfield 1994:362–363). Greenfield's aim was to pinpoint the probable grammatical capacities of the common ancestor of humans and apes.

Primates demonstrate the pairing strategy in laboratory experiments by touching cups together and combining two cups. Chimpanzee nut-cracking demonstrates the pot strategy: "Two active, moving objects (nut and stone) are combined in succession with a single passive object (anvil)" (Greenfield 1991:545). Greenfield described examples of the subassembly strategy among primates as "borderline"; possible examples include sopping water with a leaf, or inducing ants to affix themselves to a stick, and moving the subassembly to the mouth (cf. Byrne 2004, 2005). The pot strategy dominates the complex motor behavior of wild chimpanzees (Greenfield 1991:545), captive chimpanzees and bonobos, and capuchin monkeys (Conway and Christiansen 2001; Johnson-Pynn et al. 1999; Piñon and Greenfield 1994:362–363). Chimpanzees and bonobos seem incapable of constructing subassemblies to act on an object outside their own bodies (Conway and Christiansen 2001; Gibson 1990:98; Johnson-Pynn et al. 1999).

Greenfield concluded that the pairing, pot, and a rudimentary version of the subassembly strategies—and the overlapping neural wiring for both action and linguistic grammar—were shared by the common ancestor of humans and chimpanzees. She argued that language and tool use coevolved because they were controlled by shared brain structures. This resulted in an expansion of the prefrontal cortex, stimulating an increase in hierarchical complexity of combined motor actions (Greenfield 1991:550–551). Following from Greenfield's ontogenetic model, changes in early stone flaking should reflect the evolutionary development of an action grammar through subassemblies and combinations of subassemblies of ever-increasing complexity.

A MODEL OF LITHIC DESIGN SPACE

Stone tool design consists of two aspects. "Engineering" design produces techniques that cope with the latitude offered by the mechanics of stone fracture defining the boundaries of design space; and "formal" design assembles engineering techniques to produce a tool. It is useful to consider engineering techniques separately from formal design choices. Although some formal stone tool designs might be realized only by certain techniques, technique can be divorced from form. For example, the "gull wing" technique (the engineering choice) was used by some Australian Aborigines to produce stone adzes (a formal tool design) (Moore 2004) but stone adzes were also produced using other techniques (e.g., Gould, Koster, and Sontz 1971).

Stone tool replicators discover and verify sequences of engineering techniques in the context of formal types (e.g., Callahan 1985; Wilke and Quintero 1994). In this context the linkage between technique and form seems absolute because creating complex forms required complex, and often form-specific, sequences of techniques. Analyses of individual techniques are typically applied to debates about artifact form (e.g., Bradley and Stanford 2006; Straus, Meltzer, and Goebel 2005). The restrictive boundaries of design space (Van der Leeuw 2000) caused knappers in the past to independently rediscover useful techniques in the context of widely varying formal designs.

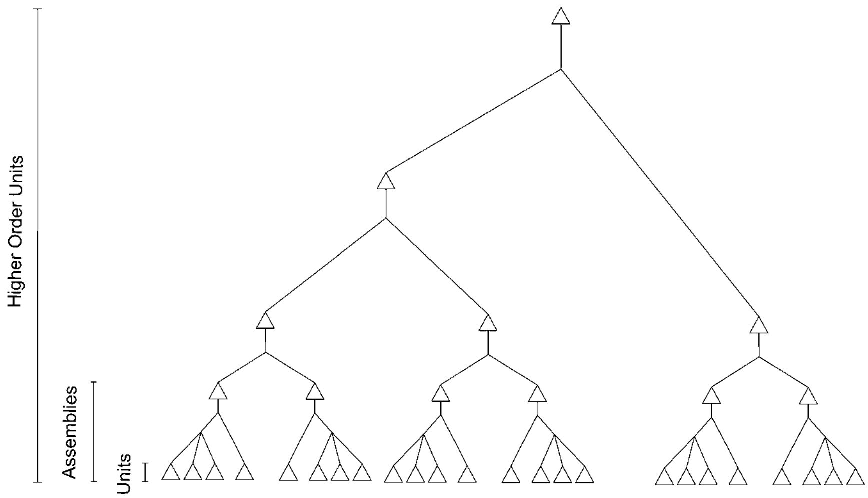
Greenfield's work shows the importance of understanding the structural aspects of how simple motor actions were arranged to produce formal designs. Holloway (1969) was among the first to seriously consider the structure of stone tool making, proposing that linguistic structure is homologous with the structure of the motor actions used in flaking. "Phonemic" motor actions are combined into techniques—low-order organization—and techniques are arranged according to grammatical rules—high-order organization—to produce stone tool forms. Low-order organization techniques are combined, according to Gowlett (1984, 1986, 1990, 1996), by rote actions into a structure called a "flake loop." Pelegrin (1990, 1993, 2005) observed that Gowlett's flake loop requires two types of "know-how": ideational know-how, or visualization, and action know-how, or motor execution. Skill at low-order organization, dismissed by Wynn as “a simple action requiring only minimal organizational ability” (1979:374), is gained through experience (Pelegrin 1993:304). Despite the pertinence of low-order know-how to accomplishing higher-order tasks (Bril, Roux, and Dietrich 2005; Roux and David 2005), research is rarely conducted into low-order know-how. Pelegrin characterized higher-order organization—Holloway’s grammatical rules of stoneworking—as “knowledge.” Similarly, Gowlett suggested that flake loops are combined according to a static “mental template” identifying the stoneworking goal (Pelegrin’s “conceptual knowledge”) and a “procedural template” that directs the removal of individual flakes (Pelegrin’s “action modalities”). Lithic studies often focus on stoneworking “knowledge,” such as the goal-driven concepts expressed in a *chaîne opératoire* (e.g., Boëda 1995; Schlanger 1996; Van Peer 1992; Wynn and Coolidge 2004) or underlying an artifact shape (e.g., Edwards 2001; Pelegrin 1993; Roche 2005).

A consensus seems to have emerged in the theoretical literature that low-order organization of stoneworking gestures is of little analytical interest. However, Greenfield’s research emphasizes the importance of studying low-order organization as a means of generating insights into evolution toward high-order complexity. The “design space” model described here explores the basic elements that underpin knapping at two levels of abstraction. The first relates to the elements’ lower-order internal structures of ideation and motor action, and the second relates to the way that elements are sequentially combined during lithic reduction.

A tree structure is used to model the organization of motor actions, following Greenfield (1991).[1] The smallest division in the model consists of ideational and motor elements and these are organized into freehand percussion “flake units” (Figure 2.2) of three types: the basic unit, the complex unit, and the elaborated unit.[2] The basic flake unit is the smallest divisible element of stone flaking because the individual motor actions that compose it are not themselves sufficient to produce flakes. Units are combined to create “assemblies,” which are in turn combined to create “higher-order units,” following Greenfield’s terminology. The way that units or assemblies are combined into higher-order units are referred to as the technology’s “architecture.”

The Basic Flake Unit

Controlled knapping by freehand percussion relies on the organization of certain motor and ideational elements. Multiple actions are carried out sequentially on the static object, Greenfield’s “pot” strategy. The resulting structure is



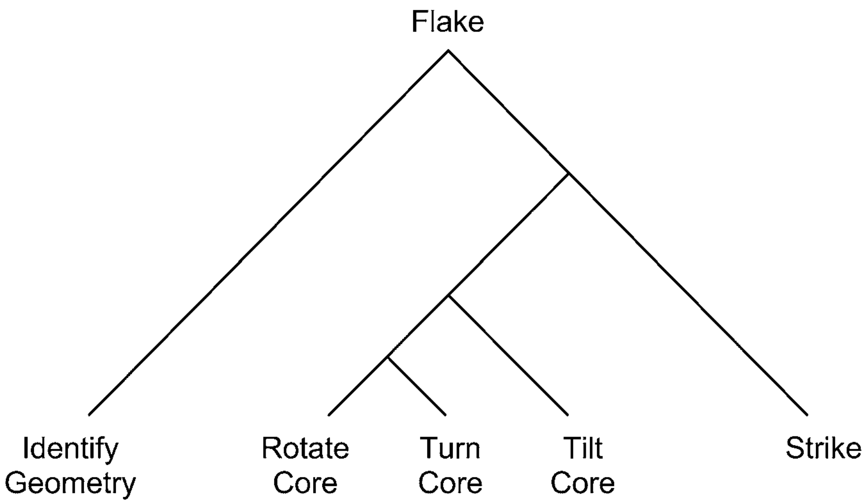
2.2. Terminology used to describe the architecture of stone flaking.

the "basic flake unit" (Figure 2.3). The basic flake unit includes three elements: (1) an ideational element that involves the identification of crucial geometric variables on the core; (2) three action elements done in response to the identification and resulting in the correct positioning of the core; and (3) a fourth action element involving the articulation of two hands to remove the flake.

The ideational element involves the recognition of an essential geometrical relationship with three attributes:

1. An area of high mass on a face of the stone;
2. A suitable platform surface located on a different face of the stone from the high mass but adjoining the high mass; and
3. Features matching 1 and 2 positioned at an acute angle (less than 90°) to one another.

Acting upon the geometrical relationship requires three actions. First, the core must be rotated until the platform surface is positioned for striking (Pelegrin 2005). This will, in many cases, require rotation of the stone between faces to get the geometrical orientations correct. Second, the core must be turned from left to right or right to left (Toth 1985a). This action positions the core relative to the arc followed by the indentor so that the impact point is behind the high mass and the force will propagate through the mass. And third, the core must be tilted in relation to the indentor arc so that the downward and outward forces (Crabtree 1968) are delivered in the correct ratio to one another. The actions



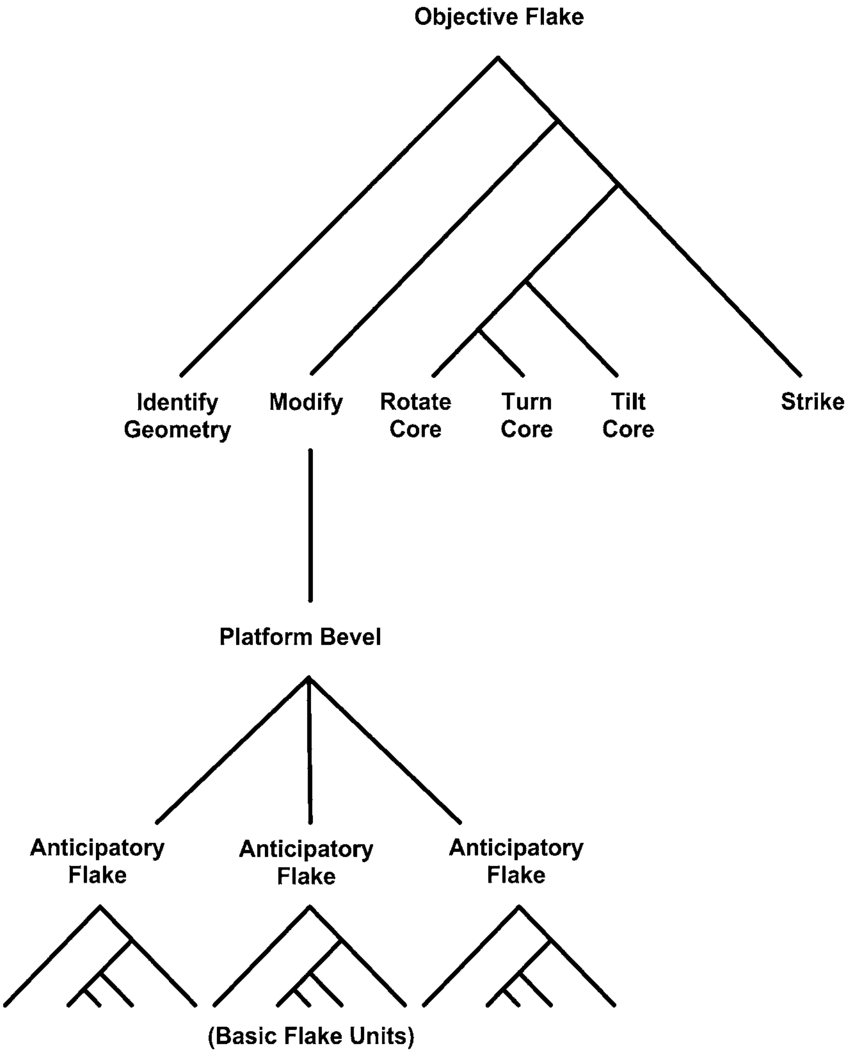
2.3. Model of the basic flake unit. The modified tree structure follows Greenfield (1991).

of geometrical adjustment involve the non-dominant hand in modern humans. Striking the flake requires the articulation of both hands, itself a complex motor task (Dapena, Anderst, and Toth 2006).

Complex and Elaborated Flake Units

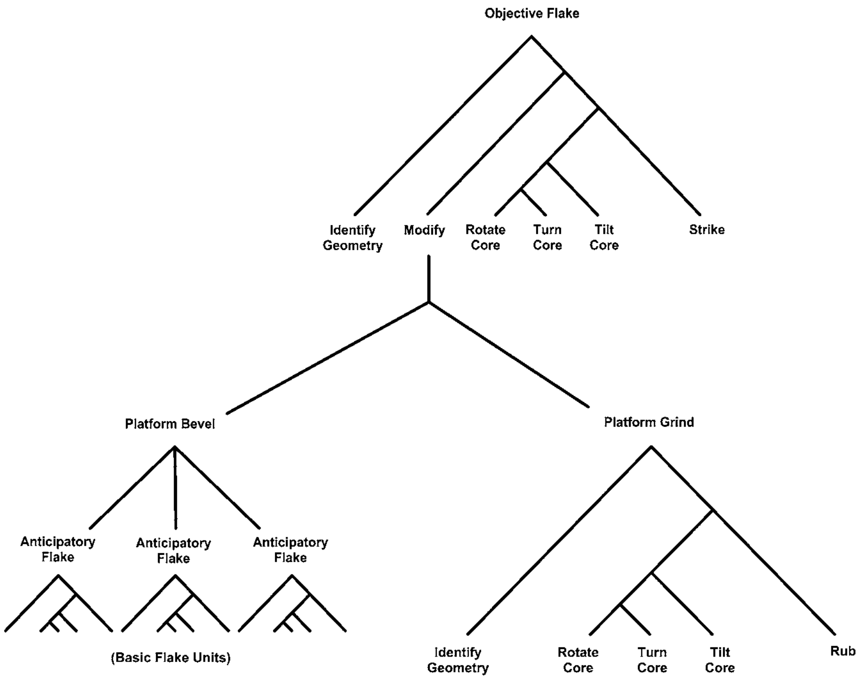
The basic flake unit is applied to zones of exploitable high mass as they are identified on the core. An increase in knapping complexity entails removing flakes to adjust the platform angle to enable the removal of otherwise unexploitable high mass, or more effective removal of high mass. Removing flakes to adjust or bevel the platform—these are "anticipatory" flakes in the sense that they anticipate "objective" removals—involves repeatedly applying the basic flake unit within a structure subordinated to the process of removing the objective flake (Figure 2.4). These are referred to as objective and anticipatory "tiers" and the resulting subassembly is the "complex flake unit."

The stimulus resulting in the complex unit's complex structure is a realization that geometrical relations can be created or improved by flaking. The knapper must recognize that platform preparation is necessary at the objective tier to trigger the actions necessary to prepare the platform in the anticipatory tier. Once this upper-tier identification is made, a series of lower-tier identifications are triggered that drive the flake removals (themselves basic flake units) that modify the platform angle.



2.4. Model of the complex flake unit.

The "elaborated flake unit" is a complex flake unit with the addition of platform grinding, shown as a branch of the subassembly to the right of platform beveling (Figure 2.5). There are a number of features of platform grinding that structurally differentiate it from platform beveling. First, the hominin must assess platform angularity, or "sharpness," as a proxy of platform "strength" or something roughly equivalent. This identification process is different from the one necessary for identifying high-mass/platform/platform-angle relationships.



2.5. Model of the elaborated flake unit.

Second, a different set of actions—distinct from the basic flake unit—are necessary to enact platform grinding. Young and Bonnichsen (1984) have shown that platform grinding involves two "behavior variables": "rub" and "shear." Third, the action of the dominant hand does not involve an "indentor arc" or similar action. A side-to-side rubbing motion, for example, is a unique one with no precedent in the gestures necessary to strike a core to produce a flake. Finally, platform grinding may have required the use of an abrasive stone distinct from the indentor and, in this case, the set of knapping tools was differentiated to form a "meta-kit." After platform beveling and grinding is completed, the upper-tier identification and actions kick in, culminating in striking the objective flake.

Combining Flake Units

The structure of flake units does not dictate the way a reduction sequence is assembled. For instance, the choice of pressure and indirect percussion involves changes in core orientation and indentor action. This has implications for tool design but it does not involve a substantial change to the structure of the underlying flake units. Similarly, the way flake units are combined into assemblies and higher-order units is independent from the complexity of a flake unit's internal structure.

The simplest building process, analogous to Greenfield's pot strategy, involves combining flake units in chain-like series rather than hierarchically. An individual flake is removed in a two-step algorithm:

> identify high mass → apply the flake unit.

A series of flake removals organized by the pot strategy looks like this:

> (identify high mass → apply the flake unit) → (identify high mass → apply the flake unit) → (identify high mass → apply the flake unit) . . . etc.

The knapping process begins anew each time the algorithm is applied, and the "identify high mass" part of the algorithm guides the progressive reduction of the stone.[3] The algorithm is inevitably applied to a novel situation because the removal of a flake always reorganizes the distribution of high mass on the core. There is presently no archaeological method for differentiating an intention to produce a particular core form by deliberately chaining together flake units from the creation of the same core form by "mindlessly" chaining together flake units. Since the removal of a flake consistently modifies the distribution of mass in the same way—the high mass is offset laterally and sometimes distally (Figure 2.6)—the result of mindless flake unit chains can look like deliberate patterning (Figure 2.7). Thus, certain core forms may be "spandrels" (after Gould and Lewontin 1979): patterns created inevitably without prior hominin intention beyond that inherent to the flake unit. This is exacerbated by the fact that many of the geometrical changes that occur inevitably in flaking are precisely those that are intentionally manipulated by modern knappers to produce effects (Moore 2005).

"Higher-order architecture" results from hierarchically combining flake units into "assemblies" and then hierarchically combining the assemblies (cf. Miller, Galanter, and Pribram 1960). In this case, flake units are arranged in complex interlocking tiers. In Greenfield's terminology, this is a "subassembly" strategy of combining motor actions. The creation of complex tool forms requires the manipulation of high-mass zones on core faces through higher-order architecture. Deliberate shaping of high-mass zones requires two things. First, during the identification process, the knapper must visualize the sort of high mass that, once removed, will create the effect. Second, the knapper must visualize how the high mass might be "constructed" (by deconstructing the existing stone) through sequential application of flake units (Figure 2.8). The internal complexity of a

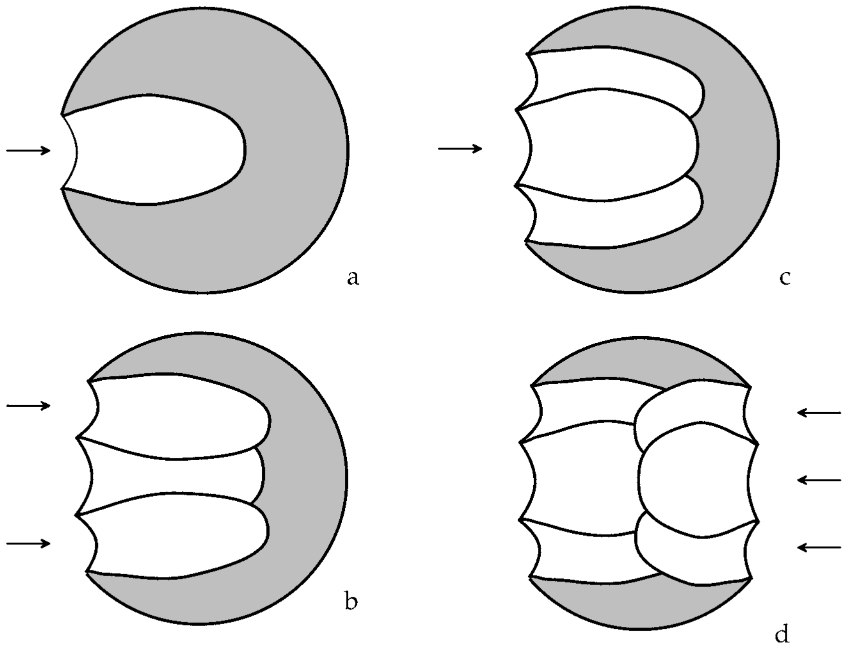
2.6. Platform view of a conjoined core-reduction sequence showing how mass relationships change in predictable ways as flakes are removed. Core reduction was by a simple chain of basic flake units. Flake 1 was struck from a natural ridge on the face of the stone, offsetting high mass to 2 and 3. Removal of 2 offset mass to 6 and 7. Removal of 3 and 4 offset mass to 5. Removal of 6, 7, and 8 offset mass to the unflaked areas marked by white Xs. The mass-offset phenomenon is a predictable effect of striking flakes from stone, but since the effect is also an inevitable one, hominin knappers did not necessarily have to make this prediction to produce cores with patterned morphologies. This is one example of the "spandrel" phenomenon in stone flaking.

flake unit is not necessarily recapitulated in the architectural strategy used to combine flake units. Basic flake units were combined hierarchically by past stoneworkers (see, e.g., Moore 2003) and complex/elaborated flake units might, in theory, be combined serially.

EARLY STONE TOOLS AND THE DESIGN SPACE MODEL

Greenfield (1991) showed that complexity in motor actions progressively evolved in hominin evolution through the pairing, pot, and subassembly strategies. The subassembly strategy dominates in human children older than twenty months, and, beginning at two years, action grammars diverge from linguistic grammars in structural complexity. Greenfield assessed that captive and wild chimpanzees and bonobos frequently used pairing and pot strategies but were only marginally capable of the subassembly strategy. Greenfield concluded that the pairing, pot, and a rudimentary version of the subassembly strategies—and the overlapping neural wiring for both action and linguistic grammars—were shared by the common ancestor of humans and chimpanzees. Subsequent hominin evolution saw a differentiation in neural wiring and increases in motor action complexity.

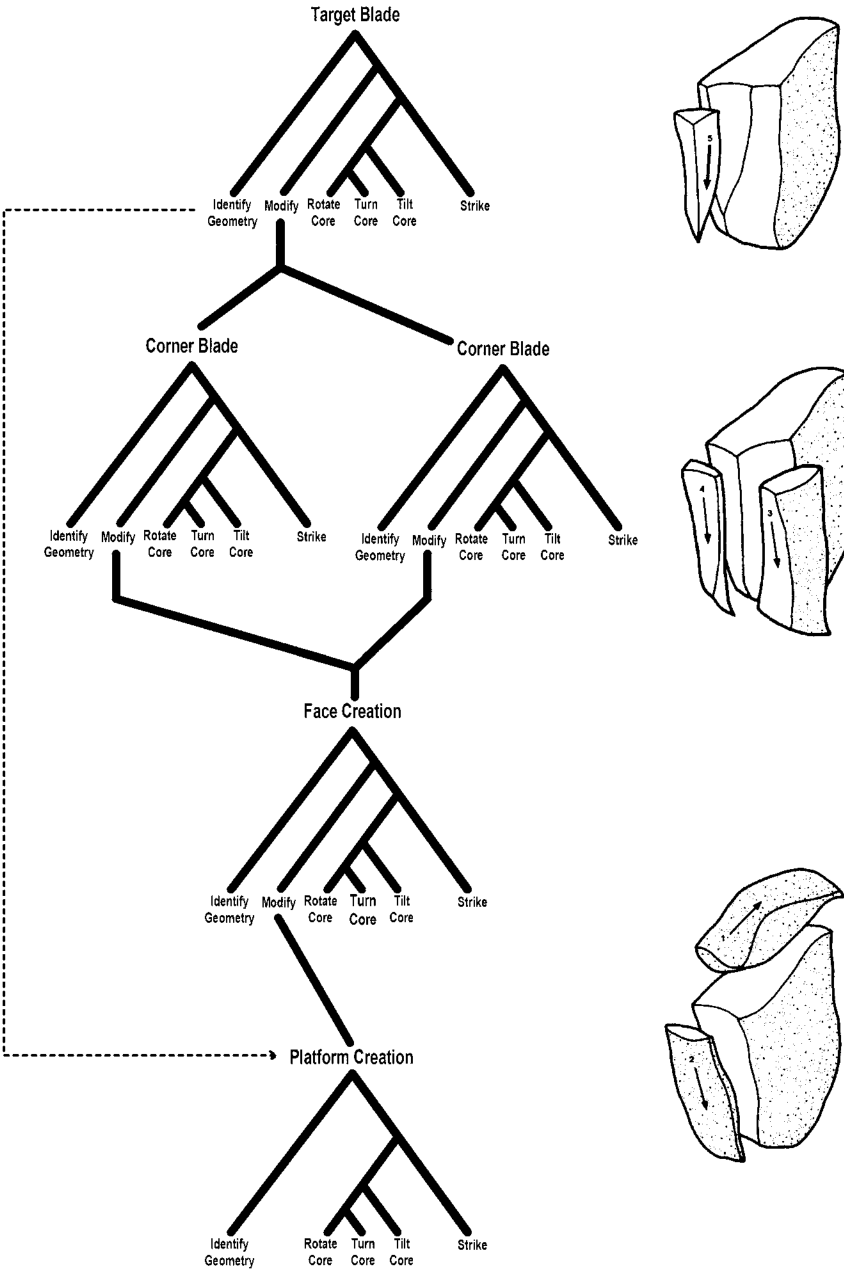
The basic and bipolar flake units, in Greenfield's terminology, reflect a pot strategy because multiple actions are applied to a static object. The earliest stone artifacts are well-struck flakes, and hominins by that stage had mastered the basic flake unit (see, e.g., Delagnes and Roche 2005; Semaw 2006). This does not



*2.7. Schematic model showing how the "mindless" process of identifying and targeting zones of high mass can create symmetrical cores. A flake is struck from a natural high-mass configuration on a circular stone, laterally offsetting the zones of high mass (*a*). Next, the offset zones of high mass on either side of the first flake scar are removed (*b*). This raises the mass between the two flake scars, which is then removed (*c*). Flakes are relatively thicker at the proximal ends, so flaking on the core's left margin offset mass toward the right margin. This is removed by a similar series of flakes from the opposite edge (*d*). This inevitable mass-offsetting phenomenon combined with removing flakes in "mindless" chains can result in a patterned core that appears to reflect hominin intent.*

indicate an increase in organizational skills because chimpanzees (and presumably our common ancestor with chimpanzees) are capable of the pot strategy (Byrne 2004, 2005; Greenfield 1991).

Sustained efforts to teach Kanzi, a captive bonobo, the basic flake unit proved unsuccessful (Toth et al. 1993). Kanzi instead invented a thrown-core anvil technique where the core was thrown onto the indentor to initiate fracture (Savage-Rumbaugh and Fields 2006; Schick et al. 1999). This is a pairing strategy where one active object (the core) acts on one static one (the anvil indentor). It would appear that bonobos have sufficiently organized motor action plans to achieve stone flaking (although the precise motor actions inherent to flake



2.8. Core reduction at Camooweal, Queensland, Australia (after Moore 2003). Basic flake units were organized hierarchically to produce an effect.

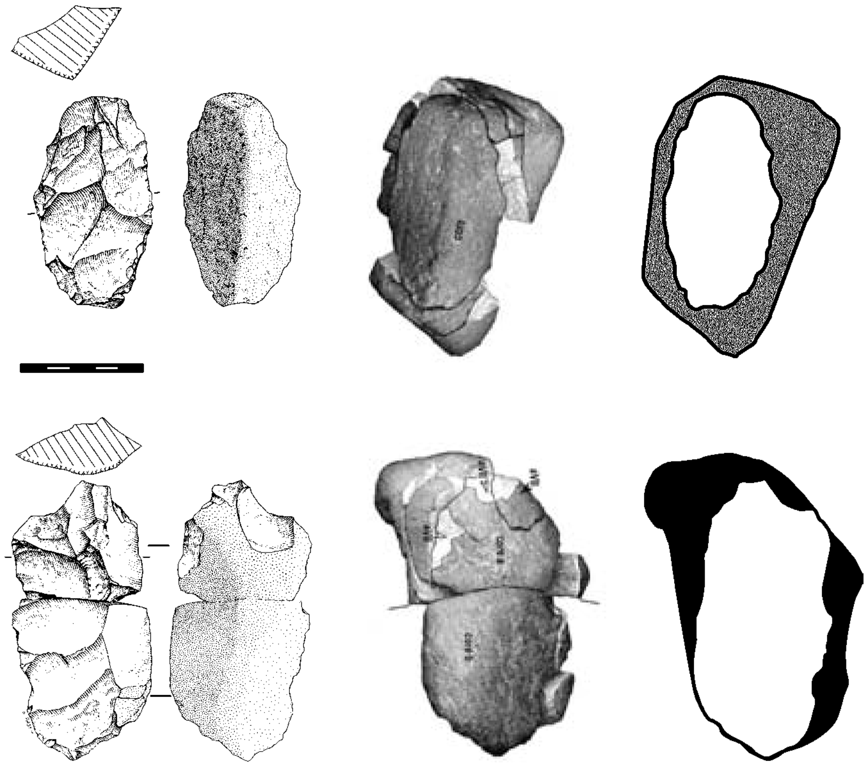
units may be restricted by anatomy [Byrne 2005:166–167; Corbetta 2005; Marzke 2005; Savage-Rumbaugh and Fields 2006:227–228]), but Kanzi was unable to recognize the geometrical relationships underpinning the basic flake unit (Schick et al. 1999; Toth et al. 1993). This geometrical identification may require different skills from those tracked by the evolution of action grammar. An ideational component like this is absent from Greenfield's model (Connolly and Manoel 1991). Since Kanzi appears to be unable to recognize and identify the essential ingredients of controlled flaking—platform angles, outward and downward force relationships, areas of high mass—we can infer, following Greenfield's logic, that our common ancestor could not either. The evolutionary precursors to stone flaking (see, e.g., de Beaune 2004; Joulian 1996, Marchant and McGrew 2005; Panger et al. 2002) are most likely to be found in the way hominins developed their ideational abilities rather than in the way that they organized motor actions (Pelegrin 2005:31; cf. Bushnell, Sidman, and Brugger 2005).

Greenfield suggested that brain differentiation that occurs after two years in human children leads to the phenomenon of "automaticity." Automatic processes are unconscious and routinized (Givon 1998; see Byrne 2005:164). As Greenfield (1998: 160) notes, "as skill increased, the lower levels of [hierarchical] organization became automatic and conscious attention came to be addressed to the higher levels." This is the phenomenon seen where students learning touch-typing first focus their attention on individual letters; then, as letters become automatic, the focus of conscious attention shifts to words; and as words become automatic, the focus shifts to sentences or thoughts (Greenfield 1998:159–160). The unconscious way skilled modern knappers apply basic, complex, and elaborated flake units is an example of automaticity; once flake units are routinized, conscious attention is focused on higher-order problems of combining units to achieve a goal. Automaticity may partly explain why researchers have devalued research into flake units, yet it is difficult to infer when automaticity first emerged in the history of stone flaking. Automaticity in applying flake units is necessary before higher-order architecture can be achieved (cf. Bril, Roux, and Dietrich 2005; Roux and David 2005).

Although the basic flake unit is built by Greenfield's pot strategy, the complex flake unit is a two-level combination (flaking to first one face, then the opposite face) reflecting a subassembly strategy. Clear evidence for a complex flake unit is seen in platform preparation to detach "predetermined" flakes in the classic Levallois method (e.g., Boëda 1995; Van Peer 1992), but complex flake units may have emerged by 285 kya in assemblages from the Kapthurin formation in Kenya (McBrearty and Brooks 2000:495–496). Complex flake units seem to be common in "bladey" technologies in the Near East after ca. 270 kya (Meignen 2007).

The elaborated flake unit is an even more complicated subassembly consisting of a complex flake unit with the addition of platform grinding. Elaborated flake units occur in modern human assemblages from the Late Pleistocene onward. Modern human knappers often use elaborated flake units combined with soft indentors to replicate Middle Pleistocene handaxes (see, e.g., Bradley and Sampson 1986; Edwards 2001; Pitts and Roberts 2000:215–222; Stout, Toth, and Schick 2006:324–325). Although the use of soft-hammer indentors has long been claimed for handaxes after ca. 900 kya (Roche 2005), few studies have documented flake unit types through detailed examination of early archaeological debitage assemblages.[4] In theory, soft indentors might be used with basic, complex, or elaborated flake units because indentor type varies independently from flake unit structure—the key attribute of the elaborated flake unit is the platform grinding. The issue is important because, based solely on organizational complexity, one might predict that complex flake units emerged before elaborated flake units.

Archaeologists traditionally track advances in cognitive evolution through stone tool morphology. Relative cognitive capacity has been inferred from tool shapes by assessing the extent to which hominins impose morphological rules on unpatterned stones (Mellars 1996). An early example of imposed form may be Acheulian handaxes because the symmetries reflected in these tools are considered the result of purposeful goal-driven reduction (e.g., Gowlett 2006; Lycett 2008; McNabb, Binyon, and Hazelwood 2004; Wynn 2002). According to this view, knappers created the characteristic symmetries of handaxes by deliberately reducing certain parts of the core more intensely than other parts. This differentially focused attention is inferred to be cognitively relevant (however, see Davidson 2002). In the model proposed here, objects like handaxes were made by chaining flake units together in a continual process of attrition rather than stacking them hierarchically. Yet the vagaries of reduction intensity and raw material shape (Andrefsky 2009; Chase 1991; Dibble 1984, 1989, 1995; McPherron 2000, 2006; Toth 1985b; White 1998) mean that both "mindless" and goal-directed flake unit chaining can create morphological patterning (Figure 2.9). Further, the "spandrel" effect in stone flaking, described previously, could be an important and presently unknown variable in pattern creation. At present there are no reliable means for inferring intent from tools shaped by flake unit chaining (cf. Monnier 2006; e.g., Moore et al. 2009). Many critics recognize that advanced cognitive processes can be reflected in tool shapes made by flake unit chains—early examples include backed microliths from South Africa, ca. 77–35 kya (Davidson and Noble 1993; Wadley and Mohapi 2008; Wurz 1999), and perhaps bifacial foliate points from various regions across Africa after ca.



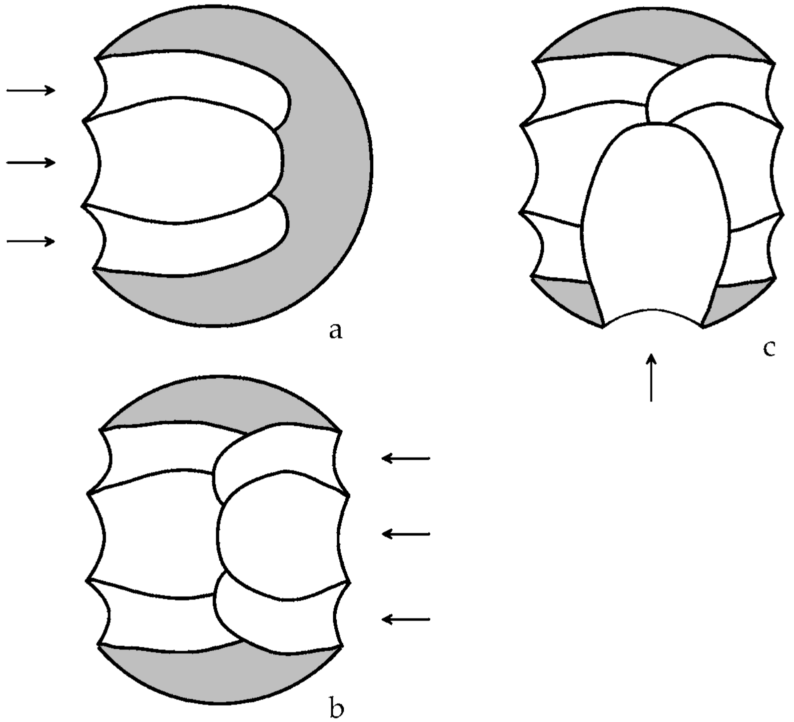
2.9. Conjoined sets of two unifacially reduced cores from the 2.34 myr site of Lokalalei 2C, Kenya (after Delagnes and Roche 2005). The conjoin sets are shown in the middle, and the image at right indicates the amount of cobble attrition caused by repeated flake removals. Core reduction at Lokalalei 2C "is unarguably geared towards the production of flakes" and "cores clearly fall into the category of waste" (Delagnes and Roche 2005:466). If so, this demonstrates that symmetrical core shapes can result from a process of chaining basic flake units together rather than from hominin intent. Scale 50 mm.

230 kya (Brooks et al. 2006; McBrearty and Brooks 2000; Shea 2006; Villa et al. 2009)—but pinpointing the emergence of this remains problematic.

Advanced cognitive abilities have also been inferred for stone reduction processes that reflect higher-order architecture. Higher-order architecture is inferred when effects generated later in a reduction sequence are contingent on effects generated earlier in the sequence by quite different configurations of flake units. Archaeologists infer intent when the contingent relationship is expressed in the same way across multiple core reduction events (cf. Pelegrin 2005). The Levallois method sensu stricto is thought to be an early example of higher-order architecture because detaching the relatively large, specially shaped "predetermined" Levallois flakes (the inferred intended product of the technique) was contingent on prior bifacial flaking to establish a specifically shaped zone of high mass on the core face (Boëda 1995; Schlanger 1996; Van Peer 1992).

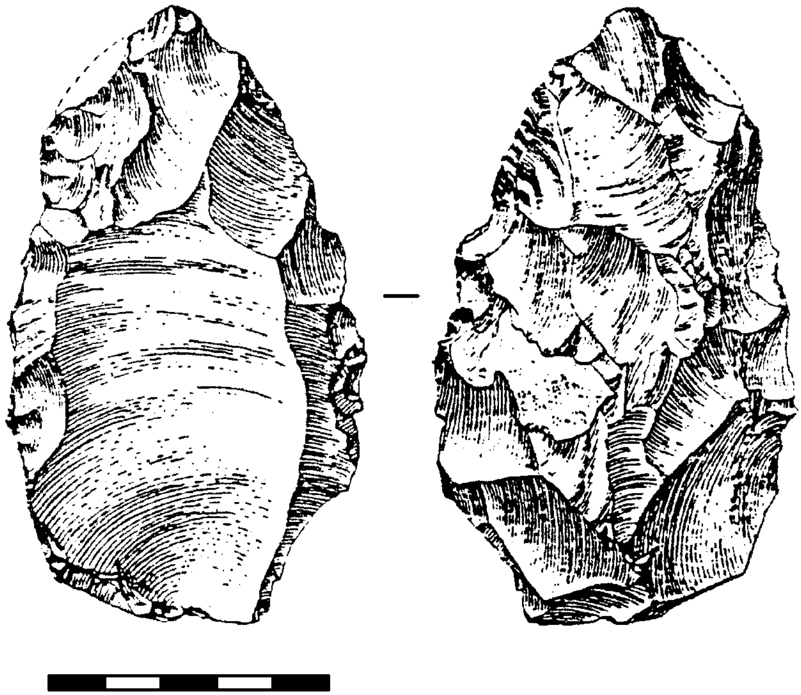
Efforts to identify earlier examples of higher-order stoneworking processes have focused on the historical antecedents of the Levallois method. In various parts of the Old World, large flakes similar or identical to "predetermined" Levallois flakes were removed from handaxes (see, e.g., DeBono and Goren-Inbar 2001; Rolland 1995; Tuffreau 1995; White and Ashton 2003). In Africa, Acheulian cleavers and handaxes were themselves made from "predetermined" flakes struck from very large bifacial cores (see, e.g., Clark 2001; Lycett 2009; Madsen and Goren-Inbar 2004; McNabb 2001; Sharon 2009; Sharon and Beaumont 2006; Tryon, McBrearty, and Texier 2006). Although the "predetermined" flake is morphologically among the largest struck from the cores in each of these cases, it is unclear how it differs in a technical sense from the flakes struck prior to it (cf. Copeland 1995). This undermines the criterion of contingent relationships among different flake unit configurations. Simple flake unit chains might produce similar results. For instance, a large-sized final flake can be a "spandrel" effect of flaking that isolates zones of high mass in a biface's center (Moore 2005; cf. Sandgathe 2004) (Figures 2.10 and 2.11). This occurs without prior intent because a flake's proximal end is usually thinner than its distal end, and hence the flake takes away relatively more mass from the bifacial core's margin than its center. When this central zone of high mass is targeted—and the mindless chain-linking flake unit algorithm predicts that it will be—a relatively large "predetermined" flake can be produced. End thinning like this occurred in biface reduction technologies throughout prehistory, and the fact that an end-thinning flake was further retouched is not itself evidence that hominin knappers specifically intended to produce flakes of this morphology (e.g., Goren-Inbar et al. 2008).[5] Bar-Yosef and Van Peer (2009) suggest that intent like that implied by "predetermination" is often assumed a priori in studies of stone reduction processes. This epistemological issue complicates the identification of the Levallois method sensu lato as an example of higher-order architecture (Davidson and Noble 1993).

Higher-order architecture has also been inferred from the presence of blade making in early assemblages. Blades are flakes that are twice as long as they are wide, and they can be produced by mindless flake unit chaining if the knapper targets elongated zones of high mass (Moore 2007; Moore et al. 2009). Nevertheless, higher-order architecture was clearly employed from the Late Pleistocene onward to carefully maintain elongated zones throughout the



*2.10. Schematic model showing how the "mindless" process of identifying and targeting zones of high mass can create end-thinned cores. Flakes are first removed from one edge (*a*), offsetting mass to the opposite edge, which is removed (*b*). Mass offset from series* B *is concentrated near the centerline of the core face, which is removed from the end of the core (*c*). In this scenario, the creation of a central high-mass zone was a consequence of reduction from opposite core margins and was not necessarily a result of "intent."*

reduction history of the core. Bar-Yosef and Kuhn (1999:329) observed that the proportion of flakes identified as "blades" increases in many assemblages by 300 kya, but it is less clear whether higher-order architecture was used to produce them. The best early evidence may be blade cores from the Near East. These assemblages, dating after about 270 kya, include cores where two core faces were knapped differently from opposed platforms oriented at an angle to one another ("twisted" or "off-axis" platforms) (Meignen 2007:135). Knapping to establish these platforms required different configurations of flake units than used subsequently to remove the elongated flakes, suggesting higher-order architecture. Blade cores recovered from the Kapthurin formation may be an African version of a similar technology (McBrearty and Brooks 2000:495–496), although this is



2.11. End-thinned handaxe (after Tuffreau 1995:418). Scale 50 mm.

not clear from the published descriptions. Complexity in higher-order architecture reached an apogee in the Neolithic period (e.g., Callahan 2006; Kelterborn 1984; Pelegrin 2006; Stafford 2003).

To summarize, knapping began in prehistory with the serial combination of basic flake units. The key breakthrough that led to early flaking was probably ideational rather than based solely on combinations of motor actions. The simple algorithm "identify high mass → apply flake unit" was applied in long chains. A serial architectural organization like this most closely matches Greenfield's pot strategy of motor action. The application of flake unit chains to create specific shapes may have emerged quite early, but this is difficult to resolve. A subsequent evolutionary step involved adding a second tier to the basic flake unit, creating the complex flake unit. The complex flake unit reflects the recognition that platform arrangements could be modified by anticipatory flaking on the obverse core face prior to removing the objective flake from the reverse face. Core faces were now hierarchically organized within the flake unit. The complex flake unit was significantly elaborated by the addition of another branch to grind platform edges. Complex flake units were in place by the late Middle Pleistocene and elaborated flake units by the Late Pleistocene, but it is possible that both were used to produce Acheulian handaxes. Up to this point in evolutionary history we see the elaboration of the internal structure of flake units, but they were linked together in simple chains. Automaticity in applying flake units likely arose early in technological evolution and was a necessary antecedent to higher-order assemblies created by stacking flake units hierarchically. Reduction sequence architecture became hierarchical in response to efforts to alter the size, shape, and location of the high mass removed by an objective flake. Blade making in east Africa and the Near East may indicate this step by ca. 280 kya. Subsequent innovations in lithic technology stem from the development of ever-more complex hierarchical arrangements of flake units, culminating in the complex stone-flaking processes seen in certain Neolithic contexts.

CONCLUSION

This study was an attempt to model the design space of stone knapping by conceptualizing the process in terms of Greenfield's "grammars of action." The form-creation process was deconstructed in line with Greenfield's findings and the model was applied to current understanding about stone tools in early hominin evolution. A trajectory of possible stages in the development of complexity was outlined. However, although Greenfield's work demonstrates that complex motor action grammars emerged among early hominins as cognition evolved, it is important to note that stone tool manufacture did not necessarily reflect maximum abilities of our human, and perhaps hominin, ancestors (Wynn and McGrew 1989). Recent research in Australasian prehistory has shown that cognitively modern *Homo sapiens* sometimes knapped stones in ways that were very similar to non-modern hominins (Moore 2007; Moore and Brumm 2007; Moore et al. 2009). Also, a historical trajectory of increasing complexity similar to the one proposed here occurred in Australia *after* the continent's colonization by cognitively modern humans. In this case, the complexity that emerged in Late Pleistocene and Holocene stone flaking was driven by social and/or environmental pressures, not by cognitive evolution (Brumm and Moore 2005). Comparing the Australasian pattern to the Old World is crucially important for identifying the various stimuli that led to complexity in stone tool manufacture.

Applying the model to the early archaeological record has reframed debates about epistemology in lithic studies, particularly about how archaeologists infer "intent" from stone tools. Deconstructing the stoneworking process has shown where aspects of our knowledge are poorly documented, particularly in relation to the specifics of platform manipulation in early assemblages. Perhaps most significantly, characterizing the reduction event in terms of combinations of flake units has raised the possibility that "mindless" flaking can lead to repetitions of seemingly complex tool forms. This is referred to as the "spandrel" effect. Isaac (1986) proposed a "method of residuals" where archaeological assemblages are compared to baseline patterns and the residual variation is interpreted in cultural or cognitive terms. Archaeology currently has no empirical baseline against which to measure the "spandrel" effect.

The mental and physical aspects of stone tool manufacture likely played a significant role in the evolution of hominin cognition, but sorting the unique aspects of this behavior from that of our hominid relatives remains a challenge (Haslam et al. 2009). This is further complicated by the theoretical and empirical issues emerging from this study. Despite the difficulties, stone tools and flaking debris are the most complete behavioral record across this crucial aspect of hominin evolution, and refining our models linking cognition and stone flaking remains an important goal of evolutionary research.

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NOTES

1. Stone knapping sits somewhat uncomfortably with the terminology used in Greenfield's model because stone flaking is subtractive whereas Greenfield's studies involved additive behaviors. Thus, a stone core is a "structure" in Greenfield's terminology. It is assumed here that the inversion of the relationship is not cognitively significant.

2. Bipolar percussion—smashing a stone on an anvil—requires a different flake unit from those applied in freehand percussion (Moore 2005). However, the simpler ideational and motor action elements of the bipolar flake unit are unrelated to freehand percussion and are less relevant for tracking cognitive evolution (see Moore 2005; Pelegrin 2005).

3. Envisioned in this way, the "plan/schema" (sensu Roux and Bril 2005) or hominin "intention" is the removal of a single flake, not the removal of multiple flakes in series. The empirical evidence of successfully produced flakes in early hominin assemblages supports the notion that actions inherent to the flake unit were coordinated specifically to achieve this effect (e.g., Delagnes and Roche 2005; Semaw 2006). However, concluding a priori that non-modern hominins also removed multiple flakes according to "plans" is

circular reasoning because it projects an approach to skilled tasks that is quintessentially modern (and the "end point" we are studying [cf. Ingold 2001]) onto our hominin ancestors (Bar-Yosef and Van Peer 2009).

4. Mewhinney (1964) traced inferences about soft-hammer flaking to the early experiments of Coutier (1929). Later experimenters reiterated aspects of Coutier's findings (e.g., Bordes 1968; Edwards 2001; Hayden and Hutchings 1989; Knowles 1953; Leakey 1934; Newcomer 1971; Ohnuma and Bergman 1982; Wenban-Smith 1989). Although these studies may indicate the use of soft indentors in biface manufacture, they do not sufficiently describe platform preparation on the archaeological specimens to confirm that early hominins applied elaborated flake units.

5. Similarly, ostensibly predetermined "Kombewa" flakes (Texier and Roche 1995) can result whenever a flake is struck from the ventral surface of another flake (Dag and Goren-Inbar 2001; Dibble and McPherron 2006; Moore et al. 2009). Ostensibly predetermined "cobble-opening flakes" ("*entame*" flakes) (Sharon 2009:339–342) can result whenever large cortical flakes are removed from a cobble.

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THREE

Insights on the Technical Competence of the Early Oldowan

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ABSTRACT

In recent decades there has been debate on the characterization of the earliest stone tool technology and its contribution to the interpretation on the origins of culture in our genus and its evolutionary relationships with other primates. Discussions have revolved over the technical competence shown in Oldowan sites and their comparison with assemblages made by chimpanzees. The nature of the early Oldowan, its implications for understanding the cognitive capabilities of the earliest knappers, and its relationships with ape tool use have dominated the debate. In this chapter it is argued that early archaeological assemblages already display a good technical control of concepts, principles, and methods associated with the mechanics of stone tool making and show an exponential qualitative leap over the use of tools by any other animal species.

INTRODUCTION

Oldowan industries older than 2 million years ago (mya) were first documented during the 1970s. Leaving aside the KBS industry from Koobi Fora—originally dated to 2.6 mya but then revised to be no older than 1.8 mya (Gleadow 1980; McDougall et al. 1980)—further sites were discovered in the 1970s for which a Pliocene chronology was proposed, such as those from Omo (Chavaillon 1970, 1976; Merrick 1976; Merrick et al. 1973) and the Gona sites (Corvinus 1975; Corvinus and Roche 1980). For more than twenty years, these sites were considered to represent a first rudimentary attempt by hominins to knap stone tools. After these early attempts during the Pliocene, it was suggested that technological skills evolved into the lower Pleistocene classic Oldowan. This view of a trial-and-error phase of stone knapping in the early Oldowan emphasized the similarities among the earliest archaeological sites and lithic debris made by chimpanzees, to the extent that the differences between chimpanzees' and early *Homo*'s technical behavior were minimized (e.g., Wynn and McGrew 1989). In the 1990s, however, new empirical evidence mainly from Gona and West Turkana has provided further data that permit an alternative assessment of the archaeological record.

In recent decades there has been debate on the definition and characterization of early archaeological sites and their contribution to the interpretation on the origins of culture in our genus and its evolutionary relationships with other genera of higher primates (e.g., Boesch 2003; Byrne 1995, 2005; Davidson and McGrew 2003; Panger et al. 2002); when and how early technologies appeared, and who made them, are questions still under discussion. Concerning who, anatomical studies have reflected upon the motor capabilities of different hominins for knapping stone (e.g., Marzke 2005; Susman 1991, 1994). Regarding when, given the fact that the earliest sites at 2.6 mya show remarkable knapping skills (Semaw et al. 2003), the existence of a hypothetical previous stage to the Oldowan, archaeologically invisible, has been proposed (Dennell 1998; Panger et al. 2002; Potts 1991). Finally, concerning how, discussions have revolved around the technical competence shown in Pliocene sites and their comparison with assemblages made by chimpanzees. The nature of this early Oldowan, its implications for understanding the cognitive capabilities of the earliest knappers, and its relationships with ape tool use have dominated the debate substantially and will be the main issues discussed in this chapter.

STONE TOOL USE BY CHIMPANZEES AND OLDOWAN TECHNOLOGIES

It is well-known that chimpanzees display a wide range of cultural activities. So far, up to thirty-nine different behavioral patterns (Whiten et al. 1999; Whiten, Horner, and Marshall-Pescini 2003) have been identified, many of them related to tool usage. Most tools manipulated by chimpanzees (branches, leaves, and other organic elements) are made of perishable materials and therefore invisible archaeologically, making it difficult to compare them with the paleoanthropological record. Given the imperishable nature of stones used to crack open nuts by some chimpanzee groups, the anvil-only technique (McGrew et al. 2003) and the hammer-and-anvil traditions (Boesch and Boesch 1983; Sakura and Matsuzawa 1991; Sugiyama 1997) permit the consideration of these activities from an archaeological viewpoint (Carvalho et al. 2008; Mercader et al. 2007; Mercader, Panger, and Boesch 2002). This diachronic perspective has triggered comparisons between Oldowan assemblages and chimpanzee stone tools (e.g., Joulian 1996; McGrew 1992; Mercader, Panger, and Boesch 2002; Wynn and McGrew 1989).

The anvil-only technique is a type of percussive technology in which the chimpanzee holds the food item in its hand and smashes it against a hard surface (an anvil), either wood or rock (McGrew et al. 2003). The chimpanzee hammer-and-anvil technique consists of the use of an active hammer (either of stone or wood) to crack open nuts placed on a hard surface (an anvil that works as a passive element), usually another stone or a tree root. As pointed out by Sugiyama (1997), the hammer-and-anvil technique is a composite activity that entails the use of associated tools; chimpanzees understand the necessary coordination for working with up to three objects, which requires considerable motor control and remarkable cognitive ability. This technique may even include one more tool, for in Bossou some chimpanzees place wedges under the anvil to keep it stable (Carvalho et al. 2008). It has been proposed that the hammer-and-anvil technique involves a fine comprehension of cause-effect relationships, suggesting a symbolic representation of objects used as instruments (Byrne 1995). This implies an intelligent understanding of the artifact and at the same time a flexible anticipation of the use of a new tool and its potential benefits (Boesch and Boesch-Achermann 2000:224).

The hammer-and-anvil technique is considered a cultural tradition and not a biological specificity (Whiten et al. 1999). Initially only documented in the subspecies *Pan troglodytes verus*, in populations west of the N'Zo-Sassandra River in Côte d'Ivoire, the hammer-and-anvil technique has now been recorded among groups of *Pan troglodytes vellerosus* from the Ebo forest in Cameroon (Morgan and Abwe 2006). It is not just a technique used occasionally but constitutes a basic element of daily life of some chimpanzees (Boesch 1993:173); it is estimated that every chimpanzee from the Taï forest uses a minimum of two artifacts per day (Boesch and Boesch-Achermann 2000). Availability of hammers, either branches or stones, is the determining factor in tool use, and their selection depends on the hardness of the nuts (Boesch 1993). There is a great variation of size and shape among the hammerstones, from small ones weighing less than a kilogram to some examples that reach up to forty-two kilograms (Boesch and Boesch 1983). The weight of hammers also varies regionally, which could be related to the size and hardness of nutshells (Sakura and Matsuzawa 1991; Sugiyama 1993).

Chimpanzees prefer stone hammers to those of wood and, when possible, those of granite or gneiss to quartzite, and quartzite rather than laterite (Joulian 1996; but see also Carvalho et al. 2008). There is a straightforward explanation for selectivity of rocks over wooden implements, as the use of wooden clubs entails up to 30 percent more effort than processing nuts with stone hammers (Boesch and Boesch-Achermann 2000). Technical variation has been identified at gender level; at Taï, adult females are more efficient than males in using the hammer-and-anvil technique (Boesch and Boesch 1984), whereas in Bossou, males perform the nut-cracking activities more often than females (Carvalho et al. 2008). In the Taï forest, where stones are scarce, rocks are valuable goods that are transported from one tree to another systematically (Boesch 1993); chimpanzees memorize the position of stones and select those that are nearer, transporting rocks over average distances of 100 meters (Boesch 1993).

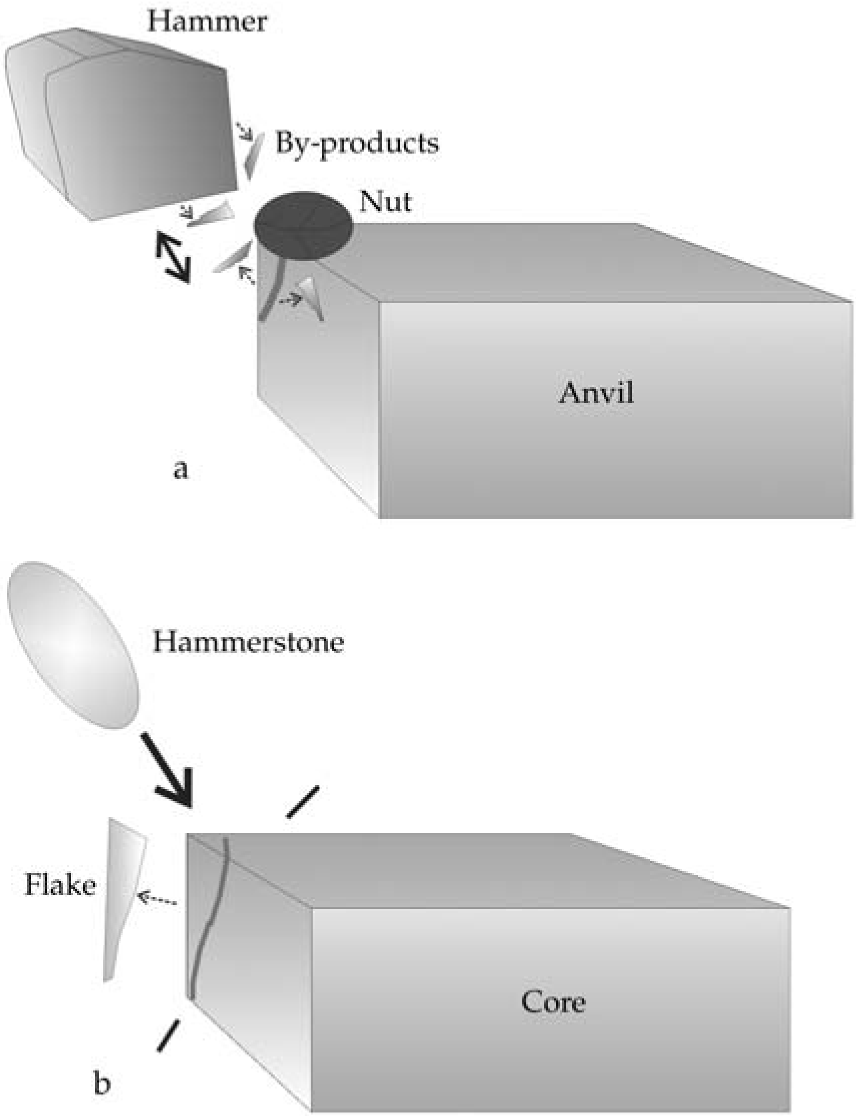
The chimpanzee hammer-and-anvil technique shows great archaeological potential. Boesch (1993) noticed the high intensity of percussion activities in nut-processing localities around fruit trees, where chimpanzees spend several hours a day. This is a social activity practiced simultaneously by a large part of the group (Biro, Sousa, and Matsuzawa 2006; Boesch and Boesch 1984) and may lead to the formation of lithic and organic residue accumulations. This is precisely what led Mercader and colleagues (2002, 2007) to excavate some of the food-processing localities of the Taï forest chimpanzees, where hundreds of stone fragments were recovered, triggering new studies focused on archaeological aspects of chimpanzee behavior (e.g., Carvalho et al. 2008; Mercader et al. 2007).

Comparisons between the hammer-and-anvil technique and the early human archaeological record have become common in the last two decades; Wynn and McGrew (1989), Joulian (1996), Mercader and colleagues (2002), and others have stressed the resemblances. They proposed that chimpanzee and Oldowan hominin skills would be similar in cultural and cognitive terms. According to this, motor and mental processes involved in the cracking of nutshells would not be very different from those involved in the knapping of Oldowan artifacts. Joulian (1996), for instance, referred to the Oldowan from Omo to stress similarities with chimpanzee material culture, emphasizing that the mechanical gestures and mental processes involved in both were nearly identical. Similarly, Mercader and colleagues (2002) compared the Omo Pliocene lithics and the Koobi Fora early Pleistocene Oldowan with chimpanzee assemblages from the Taï forest, again noting the resemblance between them.

An analysis of the technology embodied in the hammer-and-anvil technique may aid discussion on the validity of those comparisons. This technique is habitually composed of two elements, the hammer and the anvil, which chimpanzees combine to apply a bipolar force that modifies a third element, the nutshell. This requires remarkable motor coordination (Sugiyama 1997), a symbolic representation of the activity (Byrne 1995), and an intelligent understanding of the utility of artifacts (Boesch and Boesch-Achermann 2000). However, in spite of this motor, manual, and cognitive complexity, the hammer-and-anvil technique does not entail the conscious and intentional obtainment of another artifact. It is, actually, a short *chaîne opératoire*; an object (the hammer) or two (a hammer and an anvil) are used to crack open the nut and get the seed (Figure 3.1). Even if an additional element such as a wedge is included (Carvalho et al. 2008), there is no previous modification of artifacts, just the use of unmodified objects lacking intentional secondary reduction. This contrasts with any knapping activity, in which by default there is a longer and more complex *chaîne opératoire* (Figure 3.1): a tool (the hammerstone) is used to strike another artifact (the core), from which a product is obtained (the flake) that will be used afterward (e.g., to process food). Therefore, any knapping process entails one more step; instead of the direct use of an artifact, there is a production of another instrument, which is the one that will be employed subsequently.

Against this, it could be argued that *chaînes opératoires* of artifact manufacture (and not merely of direct use of unmodified tools) are familiar to chimpanzees, as they systematically modify branches, stems, and leaves in advance of their use (Whiten et al. 1999; Whiten, Horner, and Marshall-Pescini 2003). In fact, some kind of shaping associated with the hammer-and-anvil technique has also been reported (Boesch and Boesch 1993), and the use of wedges to stabilize anvils (Carvalho et al. 2008) could also be considered as an intermediate step in the task design. Nevertheless, none of these intermediate tasks seem to be a common pattern, and although they may help to facilitate the nut-cracking process, the embodied technical gestures do not change.

As well as the number of technical elements involved in one or another *chaîne opératoire*, we are dealing with different technical activities, which therefore cannot (or should not) be compared in a straightforward manner: the hammer-and-anvil technique concerns percussion processes, not flaking activities; stone artifacts are used for cracking open foodstuff, not for producing other tools. Marchant and McGrew (2005) report that chimpanzees occasionally mishit



*3.1. Diagrams of rock fracture in the chimpanzee hammer-and-anvil technique (*a*) and in any flaking activity (*b*).*

blows; thus, instead of cracking the nutshell, they unintentionally strike the anvil, from which fragments are detached. Although this accidental flake production should not be overlooked, equivalencies between knapping processes and the chimpanzee hammer-and-anvil technique remain inadequate: despite any formal similarity among their end products, the technological genesis is still different.

For these reasons, there might be methodological confusion in some of the comparisons between the by-products made by chimpanzees and Oldowan assemblages; we should not rank equally percussion by-products—stone fragments produced by nut-cracking chimpanzees during hammer-and-anvil activities—with knapping products obtained during the intentional reduction of cores. By comparing one to another in a straightforward manner, only formal similarities or differences will be obtained, since technically they originate from unrelated processes. As Kortlandt (1986) once pointed out, there is no homology or functional equivalence between the percussion activities by nut-cracking chimpanzees and the intentional production of flakes that, as accepted for decades (i.e., Toth 1982), was the main goal of Oldowan knapping.

Of course, this does not mean that comparisons between chimpanzee technology and Oldowan material culture should be avoided. On the contrary, the point is that such assessments should be based on consistent analytical criteria. In order to assess the technological value of stone by-products made by chimpanzees in West Africa, they should be compared with archaeological materials related to percussion activities. It is paradoxical that, although such percussion tools are available in the archaeological record, so far comparisons between archaeological and ethological materials have contrasted artifacts from knapping processes (Omo, Koobi Fora, Olduvai) with those involuntarily produced during chimpanzee hammer-and-anvil activities. Such comparisons are not entirely accurate and should be superseded by those that, disentangling the technological process involved in each activity, go beyond formal similarities and reconstruct the formation processes of archaeological and chimpanzee assemblages. The Lower Pleistocene sequence provides more examples of percussion activities than is usually considered, such as in Olduvai (Leakey 1971; Mora and de la Torre 2005) and Melka Kunture (Chavaillon and Piperno 2004). These case studies, alongside other beautifully preserved examples such as Gesher Benot Ya'aqov (Goren-Inbar et al. 2002), constitute a remarkable sample that still has to be compared to the material culture of West African chimpanzees.

The chimpanzee hammer-and-anvil technique has also been used to speculate about earlier technological stages to the emergence of archaeological sites. Several authors (see, e.g., de Beaune 2004; Marchant and McGrew 2005) have proposed that the earliest human stone tool behavior could have involved initially only percussion activities, in a similar way to that of modern chimpanzees. This hypothesis is suggestive, for it proposes that the emergence of stone knapping would originate in percussion activities involved in food processing.

However, it is one thing to use chimpanzee technology as a parallel source to speculate about earlier stages to the emergence of first archaeological sites, and a different one to rank ape tool use equally with Oldowan assemblages. In fact, even using chimpanzee technology to reflect on the emergence of archaeological sites is something to be done with caution: new ethological data from the New World (e.g., Visalberghi et al. 2007, 2009) report that some capuchin monkeys display a hammer-and-anvil technique not very different from that of West African chimpanzees. Some authors have used the phylogenetic proximity between chimpanzees and humans to propose that technical behavior was already present in our common ancestor some 7 mya (e.g., Panger et al. 2002). According to this argument, (supposed) similarities between the hammer-and-anvil technique and the early Oldowan would suggest that the shared hominoid ancestor to chimpanzees and hominins had those technological abilities already. However, given the report of the hammer-and-anvil technique by capuchin monkeys (e.g., Visalberghi et al. 2007), that argument loses strength; should the same phylogenetic approach be followed now, we would have to assume that technical behavior among primates emerged more than 30 mya, before the Old World monkeys and the New World *Platyrrhini* split up. This is certainly hard to support, and it therefore seems more advisable to consider the different stone tool behaviors as independent phenomena of convergence with no phylogenetic implications.

At any rate, it is not a matter of renouncing comparisons, but of knowing what we are comparing. If the aim is to compare the knapping capacities of chimpanzees with the Oldowan record, it is not appropriate to use the hammer-and-anvil technique as a parallel. Wild chimpanzees do not work stones intentionally, so in order to evaluate their knapping technical competence, we should turn to captive primate studies, in which experimental results can be compared to the archaeological record. That is precisely what Schick and Toth have been investigating in recent years with a captive bonobo, *Pan paniscus* (i.e., Schick et al. 1999; Toth et al. 1993), and their results are conclusive: in spite of some formal resemblances, qualitative differences between the archaeological and ethological samples are consistently more important than morphological similarities. The bonobo used in these experiments does not seem to control the concept of conchoidal fracture and rarely obtains products similar to Oldowan artifacts.

Therefore, apparently not even when the right comparisons are made, that is, not even when bonobos (and presumably chimpanzees) are induced to knap, do they make artifacts like those from the archaeological record (Schick et al. 1999; Toth et al. 1993). Chimpanzees show remarkable intellectual abilities and have a thorough technical knowledge, including perception of the properties of object weights, hardness of raw materials, ability to manipulate stones, and so forth. There is, however, a cognitive leap between such processes and those involved in knapping. Conchoidal fracture, typical of most knapping activities, requires an interactive association among several mental calculations, such as choice of the impact point depending on the mass, quality, and shape of raw materials; sequential use of hammerstones; direction and precision of gestures; mental image of the aimed object and so forth (Pelegrin 2005; Pigeot 1991).

Isaac (1975:29) once proposed that the qualitative leap in human technology evolution was the discovery of conchoidal fracture, a unique human trait, and not tool using, which is shared by many other animal species. As discussed in the following section, Oldowan knappers were familiar with the principles of conchoidal fracture and actually applied them in a surprisingly systematic and effective fashion. Differences from the technology executed by chimpanzees (and now also by capuchins) are, therefore, perfectly clear.

TECHNICAL COMPETENCE IN THE EARLY OLDOWAN

The technical competence of early Oldowan knappers has been debated over recent decades. In the 1970s, industries from Omo, at that time considered the oldest well-dated archaeological evidence, were proposed as the paradigm of the poor technical skills of early Oldowan hominins (Chavaillon 1976; Merrick 1976). The Omo assemblages were described as small quartz lumps smashed in an expedient fashion. This view fitted well with a unilinear scheme of technological evolution, which would begin with such simple stone tools in Omo and continue with the more structured Oldowan from Olduvai and Koobi Fora. Views on the rather limited technical abilities by Oldowan hominins were strengthened during the following years: early knappers were said to have skills similar to those of modern apes (i.e., Wynn 1981; Wynn and McGrew 1989), and a technical separation between the Pliocene and the Pleistocene Oldowan was proposed (Roche 1989).

Lokakalei 1 in West Turkana (Kibunjia 1994; Kibunjia et al. 1992) was particularly relevant in illustrating the poor technical skills during the early Oldowan; this stone assemblage showed little understanding of conchoidal fracture, so Lokakalei 1 was considered as evidence of an early stage of tentative stone-working in which hominins would not yet control the mechanics of flaking. Thus, it was considered that neither Omo nor West Turkana—at that time the only well-dated sites earlier than 2 mya—belonged to the Oldowan, but to a previous technological stage; Roche (1996) and Texier (1996) proposed the term pre-Oldowan for industries earlier than 2 mya. Kibunjia (1994) coined the Omo Industrial Complex, which would include the West Turkana Pliocene sites that Kibunjia included in the so-called Nachukui industry and the Omo assemblages, previously integrated by Chavaillon (1976) in the Shungura facies. In this view, Pliocene assemblages were characterized by violent and expedient knapping. Accordingly, the real Oldowan, in which there is an understanding of conchoidal fracture, only appears during the early Pleistocene, exemplified by classic sequences such as those from Olduvai and Koobi Fora.

Probably the vision of a Pliocene technological stage prior to the Oldowan, in which hominins experimented crudely with knapping, influenced those studies mentioned above that assimilated early archaeological assemblages and chimpanzee stone tool use. However, no matter how simple this pre-Oldowan may be, its association with chimpanzee hammer-and-anvil by-products would still be erroneous. As shown in the previous section, given the fact that most of the early Oldowan stone tools resulted from knapping activities and all chimpanzee stone by-products derive from percussion processes, any resemblance remains superficial. Furthermore, at present new data indicate that early Oldowan assemblages show technological characteristics more complex than previously thought. The concept of technologically simple industries earlier than 2 mya was based mainly on the evidence from two sequences, Omo (Chavaillon 1976; Merrick 1976) and Lokalalei 1 (Kibunjia 1994). However, the early Oldowan record now available is more abundant, with new sites in Gona, Lokalalei, and Hadar. This new evidence paints a different picture.

Even in the 1970s, industries had been discovered at Gona that could be older than those from the Turkana basin (Corvinus 1975; Corvinus and Roche 1980; Harris 1983). However, the paucity of radiometric dates and full-scale archaeological excavations was such that, until the 1990s, the Gona record had little influence on debates about the early Oldowan. Moreover, as Roche (2005) points out, stone tools recovered at Gona during the 1970s showed rather simple technological traits, which fit well with the once-predominant picture of the pre-Oldowan.

Recent fieldwork at Gona has changed that view. Semaw and colleagues (1997) reported the assemblages of EG10 and EG12, dated to 2.5 mya, and recently older sites such as OGS6 and OGS7, dated to 2.6 mya, have been discovered (Semaw et al. 2003). Not only are these assemblages the oldest archaeological sites in Africa, but their stone tools display structured technical features. First, there seems to be selectivity of raw materials, focused on the collection of better quality cobbles (Stout et al. 2005). This indicates that Gona hominins discriminated raw materials according to their knapping potential, from which it can also be deduced that knappers had a precise knowledge of conchoidal fracture properties.

Such a procurement strategy matches with the technological features of the EG10 and EG12 stone tools and suggests that hominins were well aware of the principles of stone knapping (Semaw 1997, 2000); cores were reduced unifacially, with exploitation surfaces that are worked recurrently until they lose suitable angles to continue knapping. Semaw (1997) reported flakes with dorsal faces containing an average of 2 to 3 previous negative scars and mentioned radial and parallel patterns on such dorsal faces. These are indicative of core rotation and, again, of the recurrent exploitation of knapping surfaces. Apparently, reduction of cores at EG10 and EG12 was not exhaustive (Semaw 1997), but this could be related to the proximity of sites to raw material sources (Quade et al. 2004), which would make intensification of stone reduction processes unnecessary. Description of the Gona technology (Semaw 1997, 2000) indicates a sophisticated control of stone fracture mechanics: these early Oldowan hominins had a precise and efficient knowledge of knapping processes. Therefore, in the context of the Pliocene industries at Gona (the earliest known so far), there is no place for an experimental stage of intentional stone reduction where basic knapping mechanisms were still not controlled.

In the Nachukui formation at West Turkana, where Lokalalei 1 was paradigmatic of a tentative knapping stage, new evidence at Lokalalei 2C portrays a different picture, which suggests technical variability during the late Pliocene. Although this site could be slightly younger than Lokalalei 1 (Brown and Gathogo 2002), the chronology of Lokalalei 2C remains around 2.3 mya. The superb analysis of lithic refitting in Lokalalei 2C (Delagnes and Roche 2005) has shown remarkable knapping control by hominins, where *débitage* is organized through technical rules that are repeated systematically.

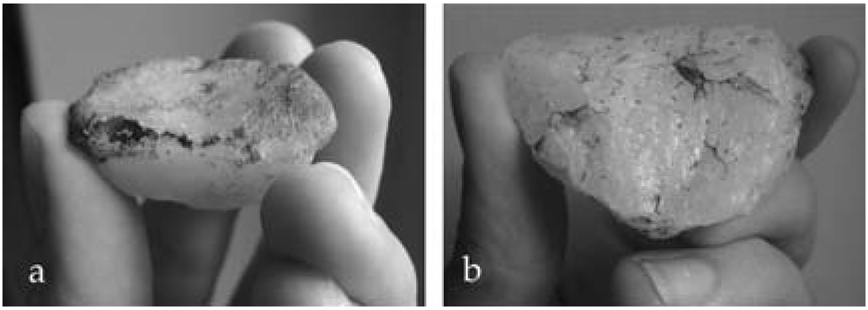
As in Gona, raw material sources are very close, and it is estimated that the Lokalalei 2C cores come from a channel about thirty meters away from the site (Harmand 2009). In spite of the proximity of raw materials, a surprisingly intense reduction of cores is documented. Delagnes and Roche (2005) report a cobble split into three cores from which at least seventy-three flakes were detached, and there are also numerous cores with conjoining sets of more than twenty flakes. Cores were usually exploited following unifacial methods, and knappers took advantage of natural angles suitable for flaking. Parallel series of flakes were obtained by the systematic rotation of cores, in which the same knapping surfaces were exploited recurrently. Such rotation does not respond to knapping accidents but to planned and recurrent decisions in the reduction of cores

(Delagnes and Roche 2005). Furthermore, knapping was flexible and adapted to the appearance of technical problems; Delagnes and Roche (2005) report core rejuvenation flakes, and reuse of fragments turned into new cores. There is also evidence of considerable motor skills such as high precision of hand and arm, as suggested by the absence of impact damage from failed blows and lack of erratic blows on inappropriate areas of cores (Delagnes and Roche 2005).

In short, at Lokalalei 2C core exploitation is extensive (average of eighteen flakes per core), recurrent (the same knapping surfaces are worked through peripheral rotation of cores until their exhaustion), precise (knapping accidents are scarce and blows are applied onto appropriate areas to obtain flakes), flexible (knappers reorganized knapping schemes as problems arose during the knapping process), and planned (there is an aim to remove flakes of a similar shape and size).

The recently reported archaeological evidence from Gona and Lokalalei 2C invites a reconsideration of the technological skills of the early Oldowan. In this new framework, the reassessment of old collections such as those from Omo, with industries dated to about 2.3 mya, has also been used to discuss the skills of early knappers (de la Torre 2004); in contrast to the view of the Omo industries resulting from the expedient smashing of small cores (i.e., Merrick 1976), Omo assemblages could also be seen as an effective technological solution to the ecological constraints imposed by the small size and poor quality of the available raw material. In spite of their small size, cores from Omo 57 and Omo 123 show consecutive scars, generally in unidirectional surfaces from non-prepared platforms but occasionally also from bifacial surfaces. This suggests that knappers made the most of the small size of raw material available and that they had the necessary precision grip for handling and accurately striking such tiny cores (de la Torre 2004).

Given the small size of cores, in Omo there are no long reduction sequences like those reported by Delagnes and Roche (2005) in Lokalalei 2C. However, to some extent it is valid to speak about recurrent reduction of cores in Omo; original sizes of raw material lumps simply do not allow sequences longer than a few flakes. In spite of their small dimensions, there are some cores showing several scars, from which well-made flakes were obtained. Furthermore, it is also possible to talk about precise and efficient knapping, given the precision grip and marksmanship required both for aiming blows with the hammerstone and holding such tiny cores (Figure 3.2). Flexibility is another characteristic of the Omo knappers, as they were adapting their technical knowledge and flaking methods to the idiosyncratic size and particular features of raw materials available in the Omo River.



*3.2. Cores from Omo 57 (*a*) and Omo 123 (*b*). In spite of their small size, these cores display several scars, which suggest an efficient precision grip by Omo knappers.*

In summary, it may be proposed that early Oldowan sites like Gona, Lokalalei 2C, and Omo share some stone knapping patterns in a chronological span close to the very emergence of lithic flaking in the archaeological record. Of course, there are also divergences. In some of the Gona assemblages (Semaw 2000), long reduction sequences do not seem to be present. This pattern could be explained, perhaps, by the proximity to raw material sources. In Lokalalei 2C, however, procurement sources are close to the site (Harmand 2009), but long sequences of exploitation are documented nevertheless (Delagnes and Roche 2005). In spite of these differences, in both sites there is selectivity of raw materials, in Gona toward higher-quality cobbles (Stout et al. 2005), and in Lokalalei 2C toward those with natural flat surfaces suitable for use as striking platforms (Delagnes and Roche 2005; Harmand 2009).

Another common feature is the flexibility of technical adaptations. In Gona, where early archaeological sites are always located near channel bars (Quade et al. 2004), raw materials were abundant and most of the stone tools were abandoned on site. In Lokalalei 2C, despite the intensity of reduction, there are missing elements in the *chaînes opératoires* that suggest some stone tools were taken away from the site (Delagnes and Roche 2005). Such flexible behavior could have been maximized in areas where raw materials were unavailable, as in the case of Bouri (de Heinzelin et al. 1999). In this area of the Middle Awash in Ethiopia, 2.5 mya stone tools were curated and transported after butchering activities, providing an example of foresight management of the landscape.

The concept of planning in stone tool making is explicitly used both in Gona (Semaw 2000) and Lokalalei 2C (Delagnes and Roche 2005), and the notion of technical adaptability to raw material availability may be also present, as proposed in Omo (de la Torre 2004). In sum, all these sites show understanding of conchoidal fracture mechanics (Pelegrin 2005) and a knowledge efficiently applied to knapping processes. Cores and flakes from Gona, Lokalalei 2C, Omo 57, and Omo 123 required elaborated mental (abstraction capacity, planning of action sequences, flexibility, improvisation) and mechanical (motor control, precision grip, accuracy) operations. The panorama is not monolithic, and there could have been heterogeneity in the level of technical competence during the late Pliocene, with some stone tool makers displaying good knapping skills (Gona, Lokalalei 2C) and others rather poor ones (Lokalalei 1). Nevertheless, the qualitative differences with respect to ape technical skills are still important.

CONCLUSIONS: ON THE CHARACTERIZATION OF THE EARLY OLDOWAN

This chapter has argued that the earliest Oldowan assemblages already show considerable degree of technological competence by the earliest stone tool makers. Further evidence to support this claim is being added gradually. In recent years, reports of structured stone tools have come from Gona (Semaw 2000; Semaw et al. 1997) and Lokalalei 2C (Delagnes and Roche 2005; Roche et al. 1999) and have been suggested in Omo (de la Torre 2004). There are more assemblages: the Hadar sites (e.g., AL-666 and AL-894), dated around 2.3 mya, show technical similarities with assemblages at Gona and West Turkana. In Hadar, there is evidence of competent knowledge of conchoidal fracture properties and organization of knapping through reasoned sequences of reduction (Hovers 2001) and raw material selectivity according to rock quality (Goldman-Neuman and Hovers 2009).

Recent finds from Kanjera, around 2 mya (Bishop et al. 2006), are also contributing to this reconsideration of the late Pliocene Oldowan. New studies report cores with recurrent exploitation surfaces not very different from those in Gona and West Turkana (Braun, Plummer, Ditchfield et al. 2009). There is also evidence of long transport distances in raw material procurement (Braun et al. 2008) and selection of rocks based upon their mechanical properties (Braun, Plummer, Ferraro et al. 2009). All of this points in the same direction. From the very first appearance of knapping behavior, hominins understood the mechanics of conchoidal fracture and applied them successfully to stoneworking.

The fact that the earliest knappers already controlled the mechanisms of stone flaking so well has led some scholars to propose the existence of a previous technological phase (e.g., Panger et al. 2002). In this archaic stage, hominins would be unaware of the mechanisms of knapping and would have attempted stone tool working before acquiring the complex technical skills displayed by Gona knappers. This stage, however, would be archaeologically invisible: during such a period of experimentation, hominins did not accumulate rocks in particular spots on the landscape, and consequently stone tools would be archaeologically inconspicuous. Once remains began to be accumulated—and therefore clusters started to be identifiable archaeologically—the tentative stage of stoneworking would lead to a new phase in which sites like Gona now displayed control of lithic flaking mechanisms.

Hypotheses on the existence of stone tool use before the emergence of the earliest archaeological sites are varied; Potts (1991) suggested that the true innovation of the Oldowan was the transport of stone resources to particular spots. According to this proposal, clustering of resources would be the main behavioral change from previous phases of human evolution; moreover, it would allow the archaeological identification of such behavior. Along the same line, Dennell (1998) proposed that at 2.5 mya, changes could have occurred in the frequency of tool use—perhaps in earlier times rocks would have only been used sporadically—and in the discard patterns of flaked stones.

Such hypotheses are appealing, as they provide an explanation for the unexpected technical control shown in the earliest archaeological stone tools by removing a sudden and punctual appearance of knapping behavior from the equation and substituting it with a gradual—but invisible—acquisition of technical skills. Nevertheless, since such models propose the existence of an archaeologically invisible stage, they cannot be tested empirically. The alternative, as reviewed in this chapter, has been to compare the Oldowan with the material culture of chimpanzees. However, Oldowan assemblages that have been used for comparisons resulted from knapping activities, whereas wild chimpanzees do not flake stones but use them to crack open nuts. Hence, some of the equivalencies that have been proposed between the Oldowan and the hammer-and-anvil technique started from a methodological confusion; if our aim is to evaluate the flaking capabilities of chimpanzees and compare them with the Oldowan, we should turn to the type of studies carried out by Toth and Schick (Schick et al. 1999; Toth et al. 1993) with captive bonobos who are induced to knap stone.

Alternatively, if the goal is to assess the technological skills of wild chimpanzees and to place them in relation to the Oldowan record, we should attempt to make coherent comparisons; it has been suggested that the real innovation of the Oldowan was the discovery of conchoidal fracture (Isaac 1975) and that Oldowan technology is based on obtaining flakes and cutting tools (Toth 1982). Even so, percussion activities could have constituted a previous technological stage to stone flaking (Marchant and McGrew 2005) and continued to be relevant throughout Paleolithic times (de Beaune 2004). Decades ago the importance of percussion processes in the lower Pleistocene assemblages of Melka

Kunture was pointed out (Chavaillon 1979), and recently their relevance has also been reported in the Olduvai sequence (Mora and de la Torre 2005). Thus, there is an abundant archaeological record related to percussion activities that can and must be compared with the material culture of West African chimpanzees.

A systematic comparison between the percussion materials used by chimpanzees and the Plio-Pleistocene record will surely shed light on the functionality of the early archaeological assemblages (Haslam et al. 2009), since—apart from remarkable exceptions like Gesher Benot Ya'aqov (Goren-Inbar et al. 2002)—the use of archaeological percussion materials is elusive.[1] At any rate, the evaluation of technical competence remains anchored to the study of knapping methods, first occurrences of which seem to have appeared about 2.6 mya. Early archaeological assemblages already show a good technical control of concepts, principles, and methods associated with the mechanics of conchoidal fracture. It cannot be ruled out that in the future even more ancient industries will be discovered and that such sites will represent those failed attempts that might characterize early stoneworking. However, that is not the case for the earliest archaeological sites currently known: knappers who made those assemblages had mastered the basic principles of stone flaking and show an exponential qualitative leap over the use of tools by any other animal species.

NOTE

1. This text was first submitted in 2007, well before the conference Paleoanthropology Meets Primatology 2: The Origins of Percussive Technology, held in October 2008. That conference fulfilled some of the claims made in this chapter and updated many of the points discussed here (Haslam et al. 2009).

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FOUR

Growing Up in the Middle Pleistocene

Life History Strategies and Their Relationship to Acheulian Industries

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ABSTRACT

From a life history perspective, it is possible to argue that the Middle Pleistocene was one of the most dramatic periods in human evolution. Paradoxically, the Acheulian industries that dominate the Middle Pleistocene record over large areas of Eurasia and Africa are often described as "monotonous" or "stagnant." In this chapter we consider the local, regional, and continental levels of variation that exist within the Acheulian, discuss alterations in life history strategies that characterize the Middle Pleistocene, and explore relationships between the two.

INTRODUCTION

From a life history perspective, it is possible to argue that the Middle Pleistocene was one of the most dramatic periods in human evolution. Paradoxically, the Acheulian industries that dominate the Middle Pleistocene record over large areas of Eurasia and Africa are often described as "monotonous" or "stagnant" (Isaac 1972, 1976, inter alia). In this chapter we discuss alterations in life history strategies that characterize the Middle Pleistocene and consider their relationship to patterning in the Acheulian. Our conclusions are preliminary and speculative but aim to address one of the more intriguing elements of the "Muddle in the Middle."

LIFE HISTORY VARIABLES

According to Zimmermann and Radespiel (2007:1163), "the life history of any species is determined by traits that characterize its developmental and reproductive rate as well as the reproductive effort spent over life." These traits include body mass, brain size, age at maturity, age at first reproduction, gestation length, lactation length, number and size of offspring at birth, neonatal weight, postnatal growth, weaning age, interbirth intervals, and life span (see, e.g., Bogin 2003; Harvey and Clutton-Brock 1985; Hemmer 2007; Lee and Kappeler 2003; Monge and Mann 2007; Zimmermann and Radespiel 2007). In paleospecies, some of these variables can be calculated directly from fossil evidence but others must be inferred using a combination of fossil, biological, and ethnographic data.

Life history variables are interrelated in complex ways. Although some traits, such as body mass and brain mass, are argued to be better predictors of overall life history than others and can be used to estimate other variables (Hemmer 2007), there is still disagreement concerning which of the life history variables or suite of variables is the most important in determining life history as a whole. For example, is brain size, age-specific mortality, or the energetic costs of growth, maintenance, and reproduction the most significant life history variable? Life history traits of a species are seen as a "predisposition toward certain ranges of potential values" that are then modified by socioecological factors (Zimmermann and Radespiel 2007:1163).

LIFE HISTORIES OF MIDDLE PLEISTOCENE HOMININS

Life history is sometimes referred to as reproductive turnover or "speed of life" (Stearns 1992). Following this metaphor, it can be said that primates have the slowest life histories of all mammals (Harvey and Clutton-Brock 1985). Specifically, primates as an order have "longer gestation periods, smaller litter sizes, larger neonates, slower postnatal growth rates, a later age at first reproduction, and a longer lifespan than do most mammals of the same body weight" (Zimmermann and Radespiel 2007:1164). Of all the primates, modern humans experience the slowest life history and differ from other primates in important ways. For instance, human infants are born relatively large but grow slowly after that with a fairly extended childhood. Humans reach reproductive age later than other primates but have shorter birth intervals, resulting in greater fecundity overall. They also enjoy increased longevity with a large proportion of this time being post-reproductive in women (Hawkes, O'Connell, and Blurton-Jones 2003; Kaplan 2002; Zimmermann and Radespiel 2007).

At what point in our evolution do we see a divergence from the pongid pattern and an emergence of what we would recognize as a human pattern of life history? This is a complex question and it seems that the development of a hominin life history pattern is best thought of as a mosaic evolution (Krovitz, Thompson, and Nelson 2003). Nonetheless, according to recent studies, the life history strategies of Middle Pleistocene hominins represent a significant divergence from pongid patterns (Krovitz, Thompson, and Nelson 2003; Tardieu 1998) and were linked to a number of other behavioral changes. Although there is debate among paleoanthropologists concerning individual behaviors, generally agreed upon traits include fully bipedal locomotion as *Homo erectus* (sensu lato) is considered to be the first obligate biped, significant extension of geographic range (Antón, Leonard, and Robertson 2002), and a shift toward more meat in the diet (Aiello and Wells 2002; Shipman and Walker 1989). This dietary shift necessitated a greater reliance on true hunting and an increased use of fire and led to hominin body proportions within or exceeding the modern human range. It also resulted in a reduction in gut size and a 20 to 60 percent increase in brain size relative to early *Homo* (Aiello and Wells 2002; Aiello and Wheeler 1995). Some researchers argue that such a significant increase in brain size in conjunction with an overall larger body size and a widening of the shoulders may have led to aided deliveries, or what is referred to as "obligate midwifery" (Trevanthan 1987; Trevanthan and Rosenberg 2000), with concomitant social implications, and to the birth of more helpless (secondarily altricial) infants (Jolly 1972, 1999, 2003; Rosenberg 1992; Trevanthan 1987; see also Walrath 2003 and comments therein; but see Krovitz, Thompson, and Nelson 2003).

Recognizing that "brain size and body size have significant correlations with a variety of maturational processes such as age at sexual maturity, maternal age at first birth and gestation length," Kennedy (2003) has argued that Middle Pleistocene species reached sexual maturity around age 13 with a female's first birth occurring somewhere between 15 and 16.5 years of age, which is within the range of modern humans. Hemmer (2007: table 19.14) presents similar inferences.

Some researchers argue that it is with *Homo erectus* that we first witness the extension of life expectancy well beyond menopause (Aiello and Key 2002;

Bogin and Smith 1996)—this is the so-called Grandmother Hypothesis, which suggests grandmothers and great aunts are involved in provisioning young offspring. This allows children to be weaned sooner and decreases a mother's interbirth spacing (Hawkes 2003; Hawkes, O'Connell, and Blurton-Jones 1997, 2003; Hawkes et al. 1998; O'Connell et al. 1999, but see Monge and Mann 2007). This hypothesis is controversial as recent studies have pointed to the lack of fossil evidence supporting it and suggest instead greater paternal investment in offspring care (Krovitz, Thompson, and Nelson 2003).

Social groups are estimated by Aiello and Dunbar (1993) to be just over 100 people (a 20 to 25 percent increase over early *Homo* group size), and some paleoanthropologists argue for increased complexity in vocal communication. At the same time, there is little evidence for the ostentatious use of symbols (Chase and Dibble 1987; d'Errico et al. 2003; d'Errico and Nowell 2000).

Although not thoroughly modern in their adaptations, the life history of Middle Pleistocene hominins represents a substantial departure from strategies practiced by apes, australopithecines, and early *Homo* and aligns them more closely with Upper Pleistocene hominins.

ACHEULIAN TECHNOLOGICAL SYSTEMS

In contrast to the life history data, the associated Acheulian industries are often described as more or less stagnant over a million years and thousands of kilometers and across a number of varied environmental settings—a "long oscillation" (Isaac 1976) with no progressive trend (Leakey 1975). Although many older schemes attempted to document a gradual development in handaxe shape and sophistication through time (Breuil and Koslowski 1931, 1932, 1934; Commont 1908; Gilead 1970), most modern workers are skeptical of such evolutionary schema, see little directional or ordered change, and take greater account of a range of complicating factors. One cannot simply assume that cruder equals older or that forms appeared and disappeared in a regular sequence. The local and regional differences that do exist are often attributed to mechanical factors such as raw material shape, type, and availability (e.g., Jones 1979, 1981; White 1998); resharpening (Jones 1994; McPherron 1994); or function (Roe 1981). In sum, the Middle Pleistocene archaeological record seems to be characterized by a technological conservatism of unparalleled magnitude, a million years of stasis usually attributed to the limited cognitive and linguistic abilities of the hominins involved (Binford 1989; Isaac 1972; Klein 1999; Mithen 1996).

We have to acknowledge, however, that part of our inability to see any trends at any scale within the Acheulian may be an outcome of poor chronological control, low-resolution signatures, and the patchy, palimpsest nature of the data. In the better understood sequences such as the Thames Valley and the Somme, the enormous time scales represented by sedimentary units, secondary deposition, and reworking would prevent the simple logging of cultural trends over long time scales if such even exist (and several generations of early workers thought they could detect it, although this may have been driven by preconceptions more than reality; see O'Connor 2007). Even the most high-resolution signatures, such as those from the stable paleo-land surfaces at Boxgrove, probably represent several generations (Pope and Roberts 2005; Roberts and Parfitt 1999). Assuming that we would be hoping to track variable scale changes—accretional changes to existing structures as well as major ruptures—the nature of the data conspire against us: any temporal trends would be rendered invisible among the jumble, small developments would be reduced to noise, and any short-lived innovations indistinguishable from chance, situation, or aberration. We are left with exactly the situation Paleolithic archaeology now finds itself in—variation largely explained by environmental factors or theoretical waxing about sociality.

We also have to accept that the level of technology that we are dealing with allows only so much modification. It is pretty incontrovertible that there is a million-year stasis in the overarching technological system, but it is also true that variation within Middle Pleistocene technology is actually more dynamic than the popular caricature. This is often lost to the prevailing negative view because general systems of analysis and synthesizing texts are more geared toward grouping assemblages into some form of manageable order than toward "embracing diversity."

At the high level, there are the well-known patterns such as the Movius Line (Movius 1948; Schick 1994) or the absence of handaxes from Europe east of the Rhine until OIS8 (Bosinski 1995; McBurney 1950; Svoboda 1989; White 2000). The non-Acheulian assemblage from the OIS11 site at Bilzingsleben (Mania 1990, 1995), where "microlithic" tools were being made while elsewhere in Europe handaxes dominated, is a prime example of how the base technology could be used in different and inventive ways, for whatever reasons. Wynn and Tierson's (1990) study showed that for the later Acheulian, continental-scale patterns do exist, with Europe, India, Africa, and the Near East all showing differences in the shapes of handaxes present (although the reasons for this and the dating of some sites may be disputed). The differential occurrence of cleavers—very common in Africa and India but largely missing from northwest Europe, is another example (White 2006). Such variation has recently been reaffirmed in Petraglia and Korrisettar's (1998) edited volume, which bore the subtitle *The Rise and Diversity of the Lower Paleolithic Record*—not words usually associated with the time period. What this has shown is that the Acheulian is *not* the same everywhere or every-when, and even if we can locate pragmatic and externally forced reasons for this, such as the type or scarcity of raw materials, hominins were nonetheless modifying their technological repertoires in different and varied ways to deal with these challenges.

Similar variation is evident at the regional level: Derek Roe's classic study of British handaxes (Roe 1968) identified seven groupings of handaxe shape, as well as variable expression of traits such as tranchet removals and twisted edges and other unique features such as the Whitlingham "burins," within that small area alone. Other studies of terrace sequences throughout Europe have shown similar variation, variation that in fact has been known since the very infancy of Paleolithic studies (Evans 1860, 1862). One must also not forget the enigmatic and still unsatisfactorily explained fluctuations between Acheulian and non-Acheulian signatures (Mussi 1995, for Italy; Vishnyatsky 1999, for Central Asia; White 2000, for Britain). How far these relate to raw materials, reduction, social practices in isolated groups, activity, or chronology is still a matter of much debate.

At the lower-scale domains variation is equally great, although paradoxically this is the level at which most people would probably assume greatest (within assemblage) homogeneity. Although most Acheulian sites admittedly seem to show a modal tendency in handaxe morphology, variation is actually quite substantial with the richer sites showing examples of practically every conceivable permutation in tool form. Derek Roe (1968), using tripartite diagrams of shape, demonstrated that there was great variation at and between sites in handaxe shape for British Acheulian assemblages. Even Boxgrove, famous for its well-made series of standardized ovate handaxes, shows higher levels of variation than popularly conceived (Matt Pope, personal communication, 2007).

In sum, when viewed from a continental, regional, or site/assemblage scale, there is far greater geographic and temporal variability than commonly projected. Tools were constantly modified for a number of reasons, which in our view boils down to at least some degree of "inventiveness" (see below). Such variation is undoubtedly dependent upon a number of factors that varied over time and space—all the usual suspects—which again betrays the idea of total monotony.

LIFE, THE HANDAXE AND THE HOMININ

The above discussion leaves us with an intriguing picture of a fractured biological and behavioral system. Hominin life history was in flux, with the emergence of several aspects of growth and development that might appear to foreshadow the "modern condition." Within (lithic) technological systems, however, we see remarkable stability over vast time periods. And, although we have emphasized that this picture conceals or subsumes considerable variation at the site level and beyond, this did not lead to change. How can we explain this decoupling? Here we offer some tentative thoughts. We start by drawing a semantic distinction between two related yet subtly different elements of change: inventiveness and innovation. We use inventiveness to describe the ability to be creative with what they had, whereas innovation is used more specifically to describe the emergence of totally novel traits.

From an adaptive viewpoint, it is possible that the initial surge of technological "innovations" that characterize the early Acheulian were enough to support post-Oldowan life history until the next major rupture. Changes in Middle Pleistocene life histories—the introduction of a childhood phase, greater levels of caregiving by old and skilled individuals, changes in mobility and terrestriality—facilitated the Acheulian and helped sustain a successful adaptation and certain level of fitness but that there was no pressure (or selection) for change exerted on the stone tools. In other words, the industries of the Acheulian were entirely fit for purpose and flexible enough to be adapted to the heterogeneous needs, strategies, or preferences of a more mobile lifestyle, responses to situation, and idiosyncrasy.

Furthermore, given the low level of technology that characterizes the Acheulian and assuming that technology changes slowly in an accumulative fashion, there are only so many modifications that could be made—many of these were at some point in time. Here we are thinking, for example, of the "precocious" use of prepared core technologies at sites such as Canteen Koppie, RSA (>1 mya; Beaumont and Vogel 2006); Gesher Benot Ya'aqov (750 kya; Goren-Inbar 1992; Goren-Inbar et al. 2000), Cagny La Garenne (OIS 12; Tuffreau 1995), and Swanscombe (OIS 11; Tuffreau 1995). Whether these arose as the accidental or inventive by-product of handaxe manufacture (Debono and Goren-Inbar 2001; Rolland 1995) or as an innovative fusion of different technological concepts (White and Ashton 2003), they are still a major and recurrent variation on the Acheulian theme. What is important is that all of these appear to be short-lived and/or geographically restricted phenomena. Inventive and even innovative behaviors may have been fairly commonplace within the boundaries of the technology, but the modifications we see either vary around a theme or, if they are more major "innovations," apparently fail to take hold until certain other thresholds were surpassed, be they cognitive, demographic, social, physiological, or a combination of these, just like the change from the Oldowan to the Acheulian. In other words, they are small steps, not giant leaps.

Based on a series of mathematical models, Shennan (2001) elegantly demonstrates that as population size increases (through either growth within a group or contact with people outside the group), so does the rate of cultural innovation and the likelihood that advantageous cultural traits will be maintained and harmful ones will be weeded out. It is likely that populations were just too small for most of the Middle Pleistocene for enduring change to take place. In other words, the feedback between the stone tools and the behavioral and developmental package of which they were a part was weak. This may be why individual variation and change seemingly has no effect on the overlying structure of the Acheulian and why the constant varieties resulting from factors such as different raw materials, idiosyncrasy, and the like did not lead to permanent or directional change. Is it that there were few mechanisms for change to spread outside a group and that local extinctions, non-linearity, and the general adaptive neutrality of many of the oscillations meant that they are not selected for?

How does this fit with recent studies that emphasize how Middle Pleistocene technology may have been socially active within the group—helping negotiate and define an individual's roles and identities (Dobres 2000; Gamble 1998, 1999)? Many such studies have concentrated on the importance of bodily gestures and techniques, but this may also be expressed within the form and sophistication of the object itself. The general stasis and lack of other overt symbolism deter us from taking this too far; most people would expect such active culture to transmute more rapidly and permanently, but, as Gamble reminds us, the object itself need not assume any overt symbolic meaning outside its original context. It also does not follow that socially active material culture within a group translates to similar patterns between groups if we consider that hominins were living in small, isolated populations with probably large exclusive ranges. The type of signaling we normally associate with material culture was possibly not necessary. There is no need to dramatically signal ethnicity during the Middle Pleistocene when no one is listening.

Mechanisms of social learning are again critical; assuming that the Acheulian tool kit was transmitted through imitation at the very least, then the strength and direction of channels of transmission will have a major impact on technological change. One might assume that greater levels of horizontal or oblique transmission might encourage wider variation and more rapid change than pure vertical transmission, perhaps suggesting that the Acheulian was passed solely from parents to offspring. However, this would be a rather simplistic view, and group size, social structure, and the social and economic benefits of conformity must all be factored into the story.

Gowlett (2005) suggested that handaxes were made throughout most of the Old World from a wide variety of materials as the result of the "artisan's choice," with the individual seen as an active decision-making agent. But the questions explicitly raised by Hopkinson (2001, 2007) and alluded to earlier remain: why did such agency not translate to innovative changes in the structure of the Acheulian, and why is there an apparent scalar gulf between them rather than the constant interplay that we see in modern human culture? It actually seems that choices operated within a tight range, variations on a theme predicated on local conditions, with the social "ties that bind" (Gamble 1999) also binding hominins to do things in a certain way. How then can this relate to human life history?

Human life history can be divided into five stages—infancy (birth to weaning), childhood (weaning to eruption of M1), juvenile, adolescence, and adulthood. According to Kennedy (2003), the childhood and adolescence stages are unique to humans (see also Bogin 2003). Childhood conveys two specific advantages. First, the development of a childhood stage coincides with a shortening of the infancy period in humans when mothers are lactating, meaning that they more quickly become fertile again, thus decreasing intervals between births (Aiello and Key 2002; Bogin 2003). Second, "the human childhood stage adds an additional four years of relatively slow growth and allows for behavioral experience that further enhances developmental plasticity" (Bogin 2003:32). Similarly, Kaplan and colleagues (2000) argue that adolescence provides additional years of development that are necessary to "learn and practice technology, social organization, language and other aspects of culture" (Bogin 2003:32). In mammals that have juvenile periods, a greater percentage of offspring reach adulthood than in species without this stage. Accordingly, it is believed that the childhood and adolescence stages dramatically enhance offspring survival.

There is general consensus that the life histories of Middle Pleistocene *Homo* included either a childhood stage for the first time or a significantly expanded childhood (Bogin 2003; Krovitz, Thompson, and Nelson 2003). The skeletal evidence points to an adolescence stage for archaic *sapiens* (Antón and Leigh 2003; Bogin 2003), although opinion is divided over whether this stage was part of *Homo erectus* life history (Antón and Leigh 2003; Bogin 2003; Tardieu 1998). This is an extremely important point because for the first time in hominin history there is additional time to learn social, ecological, and technical skills.

The duration of childhood and adolescence may have been considerably shorter in Middle Pleistocene hominins, however, as a recent study (Dean et al. 2001) based on dental evidence suggests they experienced a faster pace of development than modern humans. If childhood (and/or adolescence if present) for

Homo erectus was not actually human-like, but much shorter, would we see a pattern whereby the whole idea of a handaxe was simply too imprinted by the early learning process (a skill acquired only from parents and that might have been ultra conservative)? Could a short childhood in small groups with limited numbers of peers with whom to play, experiment, and learn new tricks be retarding true innovation? Furthermore, it may also be that there were pressures to "use this time" in other ways. Bogin (2003:38), for instance, argues that "adolescence became part of human life history because it conferred significant reproductive advantages to our species, in part by allowing the adolescent to socially integrate into the economic, sexual and political world of adults [and to] practice [these] behaviors before reproducing."

This may be the case, but to return to the notion of socially resonant technologies, we might well expect the handaxe and other tools to be implicated in such integration. If so, then the modern stereotype of adolescent rebellion against received structures could be clouding our judgment, subconsciously making us expect variation and change via horizontal routes rather than conformity. Indeed, one implication of Bogin's view is that in Middle Pleistocene hominins, the adolescent phase was a "rite of passage" into society involving the development of full relational and economic roles rather than a period during which young bucks roamed the landscape in culturally deviant groups. Given such a phase of development and its social relevance, "cultural delinquency" was probably detrimental to fitness. Combining this idea with the small, intimate, and affective networks in which Gamble (1999) envisages Middle Pleistocene hominins to have lived—where daily contact is only with kith, kin, and taskmates—then it might be that everyday elaborations on existing themes to serve immediate purposes and the refinement of already-acquired skills as a part of adolescent social maneuvering were the only socially appropriate responses.

SUMMARY AND CONCLUSION

By the Middle Pleistocene the life history of archaic hominins had diverged significantly from the pongids and, according to some authors (see, e.g., papers in Thompson, Krovitz, and Nelson 2003), came very close to a modern human pattern of growth and development. At the same time, the Acheulian and contemporary technological systems were remarkably static, and although we would suggest that this conceals higher levels of variation and inventiveness than popularly portrayed, true and persistent innovation does appear to be lacking. The challenge ahead is to seek new ways to explain this decoupling. We suggest that explanations predicated on cognitive or linguistic deficiencies are insufficient to explain what should be seen as a social or socioeconomic question. Ultimately then, we hope that the continued quest to understand why the Acheulian remained static for so long may help us to understand more about the social lives and learning environments of archaic hominins.

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FIVE

How Levallois Reduction Is Similar to, and Not Similar to, Playing Chess

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ABSTRACT

Modern cognition is more than language and symbolism. One important component of modern thinking is expertise, exemplified best in expert performances in the arts, craft production, sport, medicine, and games such as chess. Expertise is driven by a cognitive system known as long-term working memory, in which retrieval structures held in long-term memory are activated in working memory. Here they enable rapid access to large bodies of procedural and declarative knowledge that have been acquired over years of practice. Although expertise underpins many of our most esteemed accomplishments, it is not reliant on either symbols or language. In the following essay we analyze one example of prehistoric expertise—Marjorie's core from Maastricht-Belvedere. From Nathan Schlanger's (1996) description of the *chaîne opératoire* we have been able to identify many of the elements of the retrieval structure activated for knapping the core. In its overall organization this retrieval structure was no different from those deployed by modern artisans. With this analysis in hand we are then able to contrast this Levallois retrieval structure with one required for an earlier biface *façonnage* reduction, thereby tracing one link in the evolutionary sequence leading ultimately to modern expertise.

INTRODUCTION

In this chapter we argue that Levallois reduction is an example of expert performance, indistinguishable in its basic organization from expert performance in the modern world. As such, it relies on a cognitive ability known as long-term working memory, in which retrieval structures held in long-term memory, but activated in working memory, enable rapid access to larger bodies of procedural and declarative knowledge. We focus on Levallois for two reasons. First, through the work of Van Peer (1992, 1995), Boëda (1994, 1995), Chazan (1997), Schlanger (1990, 1996), and others, the *chaînes opératoires* of Levallois are now well-described and understood, providing comprehensive descriptions of a complex sequential activity amenable to cognitive interpretation. Second, the transition from the *façonnage* strategy of biface production to the *débitage* strategies of the Middle Paleolithic and Middle Stone Age has long been recognized as an important change in technological evolution (Gamble 1999). By characterizing Levallois reduction in terms of long-term working memory, we are able to contrast it with the cognitive demands of biface reduction, which required fewer procedural subroutines and, more importantly, less working memory capacity. Finally, although Levallois reduction per se does not require Theory of Mind (ToM), we explore the possibility that *learning* Levallois reduction did.

EXPERT PERFORMANCE

The title of our chapter invokes chess because chess is a familiar example of expert performance. It is also the most studied. Imagine for a moment a chess master giving a blind chess demonstration. He or she is able to play several games simultaneously while blindfolded, winning every one. How is this possible? Does he or she maintain a picture, a "mental template" if you will, of every board, with the positions of every piece? This would be an astounding feat, far beyond the human brain's normal capacity to generate and hold a mental image. Somehow the chess master is able to rapidly encode, store, and retrieve complex bodies of information. Expert performance is not limited to chess. It is the basis for the impressive improvisational abilities of jazz and classical musicians, athletic performance, acting ability, and even medical diagnosis, to mention examples commonly encountered in psychological literature on expertise.

Cognitive psychologists have long been interested in expert performance and have identified its more salient cognitive features:

1. The expert performs tasks quickly with few or no errors.

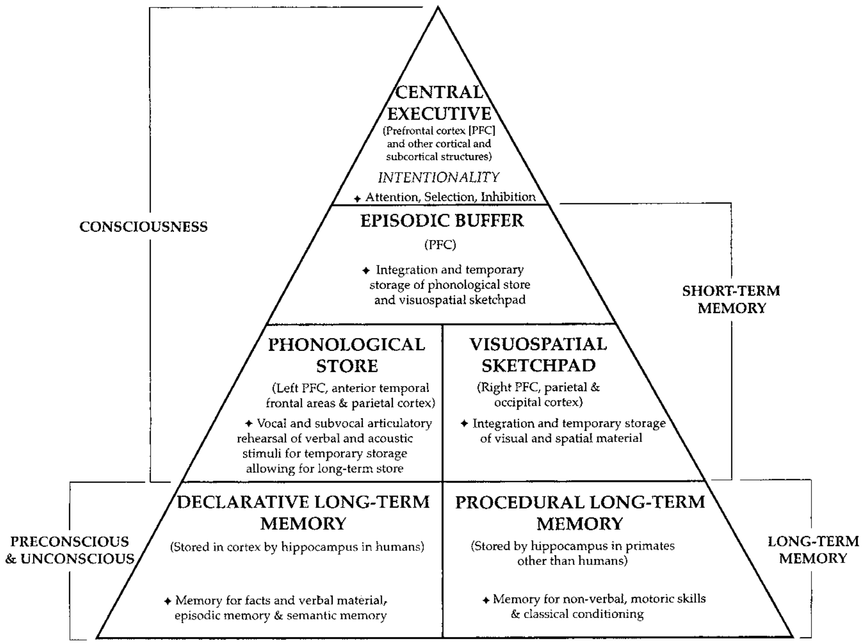
2. The expert can perform in-depth assessments of task problems with little apparent effort.
3. Expertise is largely automatic, and once initiated, it requires little in the way of active attention.
4. Expert performance is resistant to fading; the elements and sequences do not lose coherence over time.
5. The expert can be interrupted and return to the task with little or no loss of information.
6. The expert is able to learn new material and patterns very rapidly, as when a chess master learns a new opening or a jazz musician hears a new riff.
7. Expertise is limited to a narrow domain of behavior and does not transfer easily, even to related tasks (e.g., checkers or Go).
8. The expert takes years and thousands of repetitions to acquire the ability.

The psychological literature cites ten years as being the typical time it takes to become an expert.

When studying expertise, psychologists focus on exceptional individuals because they present the clearest examples of this kind of thinking. But expertise is something all of us use in aspects of our daily lives. Driving an automobile is an obvious example, keyboarding is another, and for many of us, tool use is yet a further example. Charles and Janet Keller (Keller and Keller 1996) have developed a cognitive model for blacksmithing that is a beautiful description of technical expert performance. Blacksmithing is a narrow domain of action (e.g., the abilities do not transfer to refrigerator repair or lawn maintenance). An expert smith is reliable and can be distracted and return to task, and the routines and subroutines are largely automatic. Indeed, skilled tool use is one of the best examples of expert performance. It has not received as much attention from cognitive psychologists because much of it is nonverbal, making it hard to access. It is also not as amenable to laboratory study as the less messy activities of chess masters and musicians.

LONG-TERM WORKING MEMORY

Psychologists have developed several models to account for expert performance. We find the one proposed by Ericsson and colleagues to have the most potential as an evolutionary model (Ericsson and Delaney 1999; Ericsson and Kintsch 1995; Ericsson, Patel, and Kintsch 2000). First, it is directly applicable to expert technological performance and maps nicely onto the Kellers' account of blacksmithing. Second, it incorporates Baddeley's model of working memory, which



5.1. The major components of working memory and long-term memory.

is currently the most powerful cognitive model of advanced planning abilities (Baddeley 1986, 2001; Baddeley and Logie 1999).

The concept of working memory is an elaboration of the older concept of short-term memory. Basically, working memory (WM) is the mind's ability to hold and process information in active attention. It is the basis for what are sometimes termed the mind's executive functions; its ability to plan and strategize, organize complex sequential actions, inhibit prepotent (automatic) responses, and perform thought experiments (Barkley 2001; Coolidge and Wynn 2001, 2005). This ability to hold information in attention is not a simple, single neural system but a set of interlinked abilities. Baddeley's current model consists of two independent "slave" systems, the articulatory (phonological) processor and the visuospatial sketchpad (VSSP), an episodic buffer for holding outputs of the slave system in attention, and a central executive that performs operations on the information in attention (Figure 5.1). Cognitive psychologists have established that the articulatory processor and the VSSP are independent; a task requiring the resources of one (e.g., the reading span task) does not inhibit a task relying on the resources of the other (maze memory). Information held in WM fades very rapidly, that is, it vanishes from attention unless it is repeated or rehearsed (think of retrieving a telephone number from the book but getting distracted before you can punch it into the telephone). In fact, WM attention is only a few seconds in length. Both the articulatory processor and the VSSP have neural systems that allow information to be rehearsed and refreshed, but both are still vulnerable to distraction. A new WM task will inevitably erase the old information—except in domains of expert performance (Baddeley 2007).

Long-term memory (LTM) is the ability to store information for hours, days, or years. In humans the hippocampus plays an active role in transferring memory traces to LTM, but the LTM traces themselves are stored diffusely in the neocortex, largely in the temporal lobes (Gazzaniga, Ivry, and Mangun 2007). Cognitive psychologists distinguish between two kinds of LTM, declarative and procedural (Baddeley, Eysenck, and Anderson 2009). Declarative memories are verbal memories that can be expressed (by humans) in words. Procedural memories are largely sequential motor procedures, such as those required in performing sports, housework, or most aspects of tool use. It is often difficult or impossible to verbalize procedural memories. Episodic memories are memories of episodes in an individual's past (Tulving 2002). They are generally placed with declarative memories because of their implied image content, but it is almost certainly the case that episodes also carry procedural content. Information is not easily transferred to LTM unless it has been associated with an episode of high emotional valence (where were you when you heard about the 9/11 attacks?). Procedural memories, especially, require repetition in order to be consolidated into LTM. Complex motor tasks, such as hitting a baseball or playing a scale on a violin, require many, many repetitions and constant practice. But so do some declarative memories, the complex mid-game patterns of chess being a good example.

Expert performance has features that seem to violate the usual constraints of working memory. The blindfolded chess master can hold game #1 in attention, shift to game #2, and then back to game #1 without losing information. Any image of game #1 should have been lost from WM, but there were not enough repetitions, or time, to transfer them in the normal way to LTM. This has long been the puzzle of expert performance. Ericsson has proposed a solution that incorporates elements of both WM and LTM, along with a cognitive shortcut he terms a "retrieval structure." A cue is a memory trace that is linked by association to a much larger set of memory traces. In our chess example, "Sicilian defense" would be a cue linked to larger body of information that includes the exact positions of thirty-two pieces on the sixty-four squares of a chessboard. Our blindfolded master need only recall, initially, that game #1 is Sicilian defense. A "retrieval structure" is a comprehensive set of cues that the expert learns and files away into LTM. When faced with the blindfolded demonstration, or any chess game, the master accesses the retrieval structure and deploys its cues as necessary. A cue, then, is a memory trace activated in working memory that provides a direct access to a much larger, more comprehensive set of information held in LTM. Cues and the retrieval structure also allow the expert to transfer new information rapidly into LTM, because the framework and cue associations are already in place. Of course, a retrieval structure is not easily acquired. A master-level retrieval structure in chess requires years and countless games to acquire. Once acquired, they enable quick, flexible responses to a huge array of specific problems. But the retrieval structure is not transferable. A chess master is no better at the game of Go than any other beginner because he or she has not formed the necessary retrieval structure. An expert retrieval structure underpins the impressive performances of musicians, medical diagnosticians, dancers, and orators. But one also underpins activities we consider mundane because everyone can do them—driving an automobile, sautéing onions, dribbling a basketball. LTWM is a style of thinking we all do in our own domains of expertise.

Tool use is a procedural skill that relies on retrieval structures. Much like a chess master approaching a game, an artisan approaches a task by activating an elaborate retrieval structure that has been learned and consolidated over years of practice. Some of the cues in this structure consist of simple declarative information—names of objects, materials, and tools, for example. But the majority of the retrieval structure consists of visual and aural images, and even muscle and postural cues. Technical retrieval structures consist largely of visual patterns, tactile and aural images, and procedural memories. A technical task constantly changes in its parameters; indeed, a feature of any task requiring expertise is the dynamic nature of the goal itself. In chess the opponent moves, in jazz improvisation other musicians play, in blacksmithing the very chemical nature of the material changes. The expert retrieval structure contains a huge range of alternative procedures that can respond to rapidly changing conditions. They are not held in attention but can be activated instantaneously when an appropriate cue appears in the task. Technical tasks such as blacksmithing invoke a dynamic interplay between short-term, intermediate steps in a task and the set of cues activated in attention. The Kellers use the term "constellation" for this activated body of knowledge, but a constellation is clearly an activated retrieval structure by another name. When a portion of a retrieval structure is activated in the same way on numerous occasions, it requires less and less active attention. The Kellers term such automatic constellations "recipes." They can be activated and deployed with minimal demands on attention or executive function—very similar to the execution of an opening by a chess master. Although recipes are largely rote routines, retrieval structures are not invariant. In fact, they enable the artisan to respond quickly and flexibly to a large range of potential circumstances.

Even though the vast majority of the declarative and procedural information of a retrieval structure is held in LTM, it is activated in WM, and thus working-memory capacity is relevant to expert performance. Novices in any field of endeavor have difficulty because initially all of the information must be held in attention. They have not yet transferred procedural sequences to LTM and have little or no framework for rapidly transferring new information to LTM. They have not consolidated a retrieval structure. Over time they establish one and add to it through experience and practice. As their retrieval structure becomes more powerful, flexible, and automatic, it places fewer demands on working memory. The freed-up capacity in WM is then available for other tasks, including a deeper analysis of the task at hand, or even daydreaming. The artisan can activate other jobs from memory or unrelated tasks, and one potential result of this is conscious experimentation and innovation (Shah and Miyake 2005).

LEVALLOIS

It is unremarkable to assert that Levallois reduction is an expert performance. A skilled stone knapper producing a series of Levallois flakes meets all of the criteria of expertise. He or she can perform the task quickly, make almost no errors (other than those caused by flaws in the material), and perform a complex in-depth assessment of the task with little apparent effort. Moreover, mastery takes years to acquire and is developed only within the relatively narrow domain of stone knapping. It does not even transfer to other technical domains. Assuming that prehistoric knappers followed the same procedures as those identified by Boëda, Van Peer, Schlanger, and Chazan—and there is no reason to doubt these reconstructions—then Levallois is perhaps the best example of expert performance in all of lithic reduction (Boëda 1994, 1995; Chazan 1997; Schlanger 1990; Sellet 1995; Van Peer 1992, 1995).

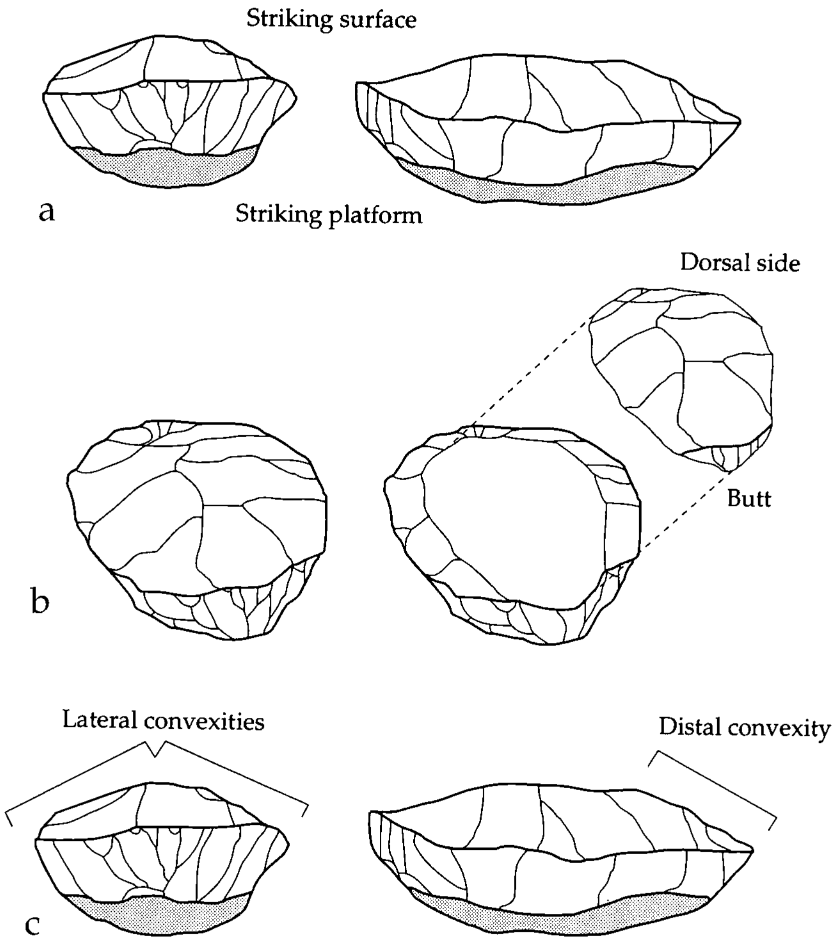
It is slightly more controversial to assert that the cognitive organization of the procedure is indistinguishable from the cognitive organization of modern technical activities, but we think this is defensible. The concepts developed by the Kellers to describe blacksmithing are directly applicable to Levallois reduction, as is the model of long-term working memory. Nathan Schlanger's excellent description of the reduction of Majorie's core provides a convincing example (Schlanger 1996).

Whether we consider Levallois to be a "concept" or a "strategy," all authorities agree that knappers using Levallois approach the task with an overarching plan/goal that guides the reduction of the core. The Kellers use the term "umbrella plan" for the overarching plan/goal that a smith brings to a task, and this is an apt term for the knapper as well. The Levallois umbrella plan consists of the immediate conditions of the task—the size and condition of the core, the ultimate task for which the products will be used, the time available, other knappers in company or within hearing—along with all of the declarative knowledge (*connaissance*) and skill (*savoir faire*) acquired from previous tasks. The umbrella plan consists of all of the considerations brought to bear on a specific reduction task. From these the knapper can generate specific sequences of action, which the Kellers term "constellations."

Levallois reduction consists of sequences of routines or constellations, each of which has discrete subroutines. For each Levallois sequence the knapper must prepare a production surface, which is the shallow convex surface from which a single flake or multiple flakes will be removed. The knapper must attend closely to the distal convexity—opposite the future striking platform—and the lateral convexities because these guide flake propagation. Schlanger suggests that the choice of distal convexity determined much of what followed, a conclusion echoed by Sellet: "The decision concerning the direction of the main Levallois removal was done very early, maybe before preparation of the Levallois surface, for some cores in an early stage of preparation show a clear emphasis on the preparation of the proximal end" (Sellet 1995). The knapper must also prepare the platform surface, which is more convex but retains the mass of the core (and constrains subsequent subroutines). The platform surface includes the striking platform itself, which must be prepared to create an optimal angle and curve for the subsequent Levallois removal. After all of this preparation, the knapper uses percussion to remove a single flake (in preferential Levallois) or multiple flakes (in recurrent Levallois) (Figure 5.2).

This single routine is made up of at least three distinct subroutines—production-surface preparation, platform-surface preparation, and platform preparation. These need not be sequential in time, but they are hierarchical, in the sense that the production-surface preparation takes precedence over the others. There is considerable feedback between the subroutines, and the entire process is dynamic and interactive.

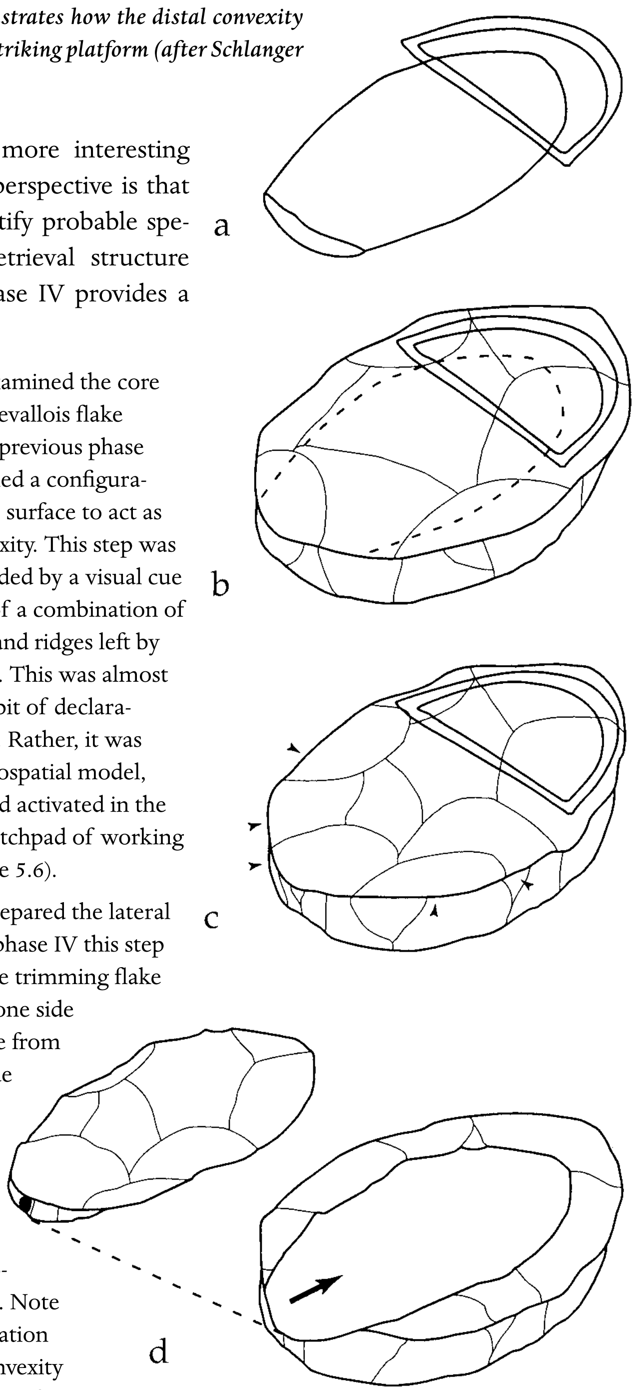
After final flake removal the knapper could start anew and prepare a new production surface, platform surface, and platform. This would constitute a separate sequence or routine. From his analysis of Marjorie's core Schlanger became convinced that the knapper's first step in the new sequence was selection of the distal convexity of the production surface (Figure 5.3). This choice channeled all of the subsequent subroutines of the sequence. Of course, for each succeeding



*5.2. The asymmetrical surfaces of a Levallois core (*a*); striking surface and idealized Levallois flake (*b*); the locations of lateral and distal convexities (*c*) (after Boëda 1994).*

Levallois routine, the core becomes progressively smaller, presenting a different set of problems. All of the authorities on Levallois agree that the knapper adjusts the subroutines so that the final flakes are as large as possible. Schlanger presents a telling graph of flake sizes from Marjorie's core. Even as the core reduced in size, the resulting Levallois flakes remained large. This could only occur through significant adjustments in the subroutines (Figure 5.4).

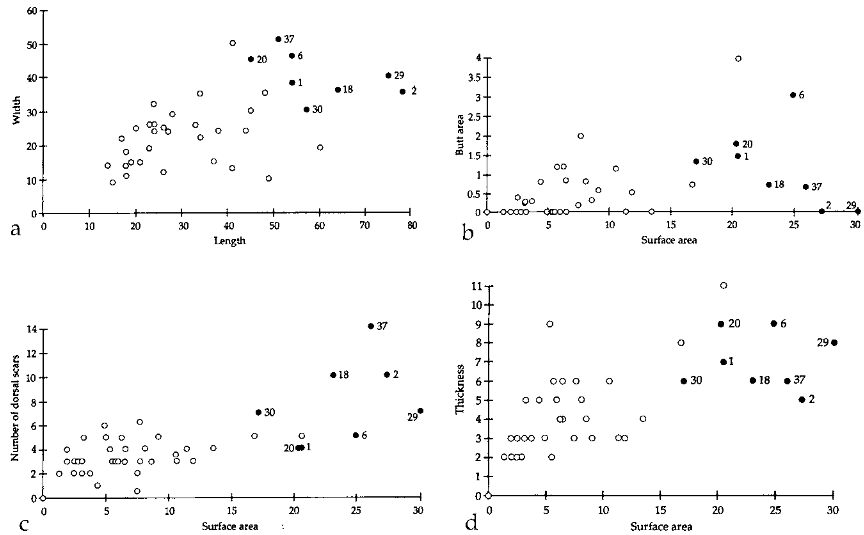
Schlanger's analysis of Marjorie's core revealed six discrete phases of Levallois reduction (the earliest phase is not clearly represented) (Figure 5.5). Each of these routines or constellations breaks down into a number of discrete



*5.3. Series (*a–d*) demonstrates how the distal convexity governs location of the striking platform (after Schlanger 1996).*

steps. But what is more interesting from our cognitive perspective is that it is possible to identify probable specific cues in the retrieval structure itself. Reduction phase IV provides a good example.

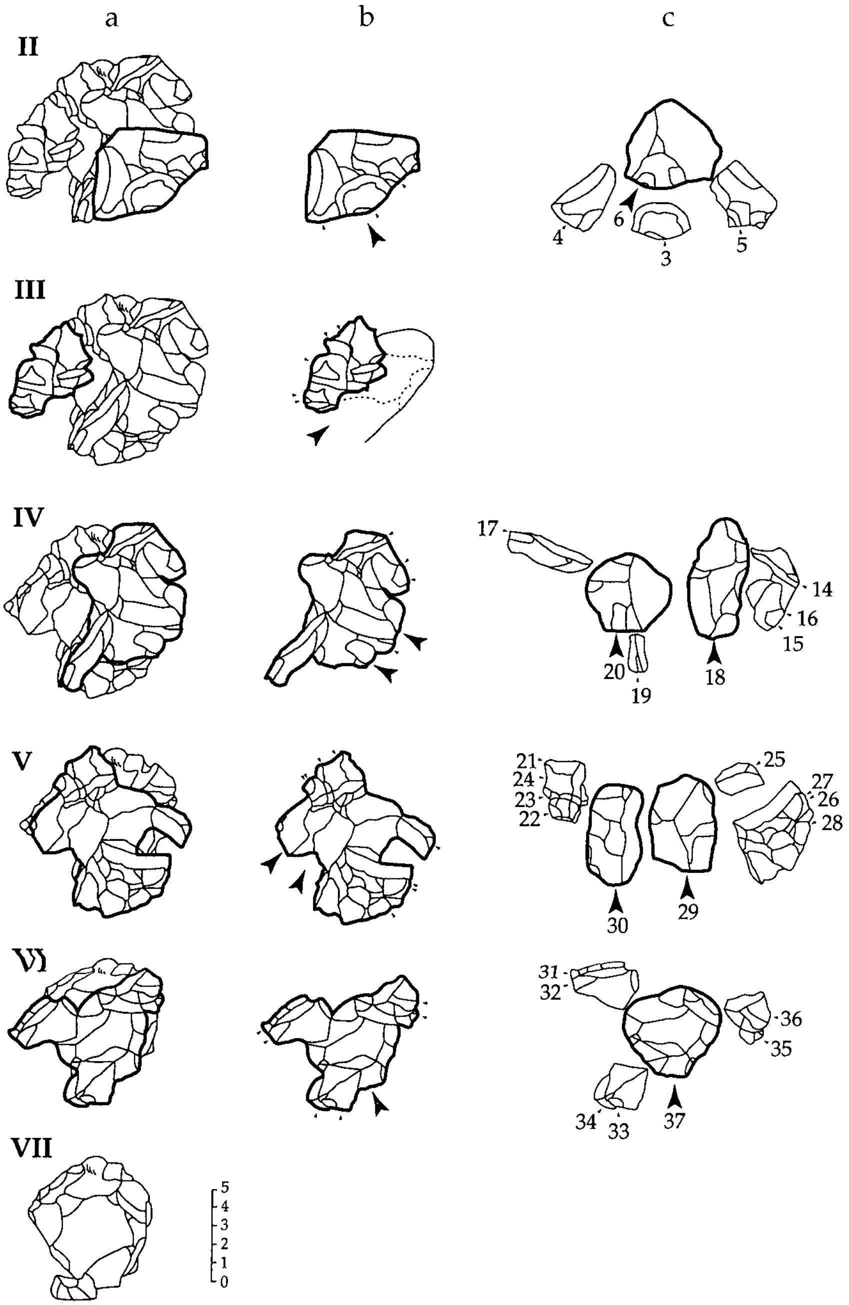
1. The knapper examined the core after the final Levallois flake removal of the previous phase (III) and identified a configuration of the core surface to act as the distal convexity. This step was very clearly guided by a visual cue that consisted of a combination of surface profile and ridges left by previous action. This was almost certainly not a bit of declarative knowledge. Rather, it was probably a visuospatial model, held in LTM and activated in the visuospatial sketchpad of working memory (Figure 5.6).
2. The knapper prepared the lateral convexities. In phase IV this step involved a single trimming flake removed from one side (#17), and three from the opposite side (#14, #15, and #16). These modifications produced an appropriate production surface. Note that no modification of the distal convexity occurred. Its identifica-



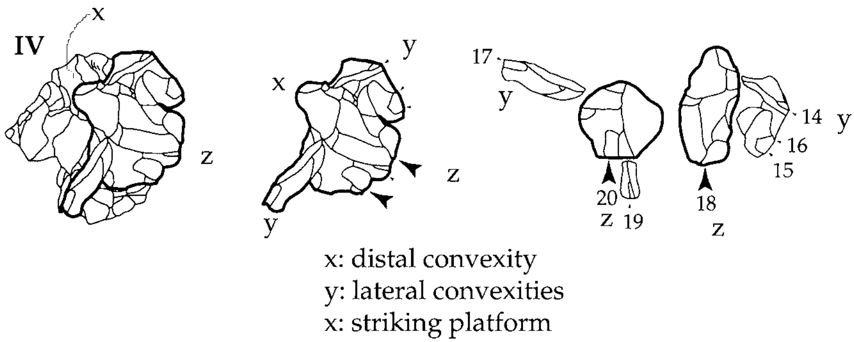
5.4. Four charts that situate the Levallois flakes of Marjorie's core in relation to other flakes of the core. Of particular note is that the later Levallois flakes are not smaller than the early ones, suggesting that the knapper continually adjusted his or her technique to maximize surface area of large Levallois flakes. This does not require any "visualization" of the final product (after Schlanger 1996).

tion was the first step in the phase. At least two cues are evident in this step, one guiding the lateral convexities specifically and a higher-level cue guiding the production surface as a whole.

3. The knapper prepared the striking platform, trimming an appropriate angle and an appropriate curvature onto the platform surface opposite the distal convexity. Platform angle and curvature are cues, and indeed platform configuration was itself probably a higher-level cue incorporating several specific cues. Again these cues were probably accessed in the VSSP of WM.
4. The knapper struck off a Levallois flake (Figure 5.6, #18). The platform configuration produced in step 3 acted as a cue to guide this motor procedure.
5. The knapper examined the core and saw that Levallois flake #18 had not exhausted the propagation potential of this series. The cues were probably the same as the higher-level cues in steps 3 and 4 that assessed production and platform configurations.
6. The knapper struck off a small non-Levallois flake to flatten the convexity left behind by the removal of #18. This procedure could have been guided



5.5. From top to bottom, the six reconstructed phases of Marjorie's core's reduction (after Schlanger 1996).



5.6. Phase IV of the reduction sequence, with distal convexity* (x)*, lateral convexities* (y)*, and striking platform* (z) *labeled (after Schlanger 1996).

by the higher-level production surface cue or perhaps a separate cue called up just in these situations.

7. The knapper re-prepared the platform, guided by the same cues as deployed in step 3.
8. The knapper struck off Levallois flake #20.
9. The knapper examined the core again and searched for a new distal convexity.

Schlanger also identified an interesting pattern that played out in the successive phases. For each succeeding phase, the distal convexity and axis to the new striking platform were oriented at right angles to the axis of the previous phase. This may have been the knapper's usual procedure, perhaps based on a shared norm in this knapping community, or it might have simply been fortuitous.

From our cognitive perspective, phase IV appears to have been guided by at least seven different cues, some of which were components of others:

1. Distal convexity
2. Production surface
2a. Lateral convexities
2b. Location of striking platform
3. Striking platform
3a. Location of distal convexity
3b. Angle
3c. Shape
3d. Ideal point of percussion

In Schlanger's terminology these constitute an "integrated ensemble"; in the Kellers' terminology they would be part of a constellation. But from the perspective of expert performance this was clearly a retrieval structure that guided the action by facilitating rapid access to more complex encodings held in LTM. These encodings included models of visuospatial configurations learned during knapping apprenticeship and motor procedures for accomplishing each step in each phase. Note that no "mental template" was required. Instead, specific visual cues on the core facilitated access to models and procedures held in LTM. This is recognition, not imagery.

Certain features of the retrieval structure that enabled Marjorie's core are significant for a study of cognitive evolution. Even though the reconstruction has identified relatively few of the total cues that must have been involved, it is still possible to identify features of the organization of the retrieval structure itself. First, it was hierarchical, in the sense that some cues were components of, and elicited by, higher-level cues. The "production surface" elicited "distal convexity," "lateral convexity," "position of platform," and so forth, and each of these elicited more specific cues made of angles, surfaces, ridges, and so on. Second, cues clearly changed according to their role in the procedure. What was a lateral convexity in one phase became a potential distal convexity in the next. Such flexibility is one of the characteristics of expert performance. Finally, and perhaps most significantly, the phases of reduction in Marjorie's core were not independent of one another. The knapper apparently conceived of a sequence of phases in order to maximize productivity of the core and, while completing one phase, was looking ahead to the next. This latter ability requires not just the retrieval structure of LTWM, it also requires the active attention of working memory to keep the near goal and ultimate goal in mind at once.

How Levallois Reduction Is Similar to Chess

The hominin who knapped Marjorie's core used a form of cognition that today is still the basis for expert performances of all kinds. It included an in-depth analysis of the task at hand, was flexible, responded dynamically to changing conditions, and consisted of a large number of specific procedures and recipes. It fits easily into models of expert craft cognition and, in its organizational features, resembles other expert domains, including chess. As in modern chess, the knapper of Marjorie's core relied on specific cues in the task to access appropriate long-term procedural memories learned over years of practice. Working memory did play a role in monitoring the condition of the core and assessing the impact of current action on future steps, but the procedure itself was almost entirely a matter of long-term working memory.

How Levallois Reduction Is Unlike Chess

From a cognitive perspective, Levallois reduction also differed significantly from chess. Even though one could argue, metaphorically, that the knapper had a dialogue of sorts with the core, a chess player has a very real opponent (even when it is a computer). To be successful, a chess player must predict an opponent's possible responses, and this requires a theory of mind (ToM), the understanding that another individual has mental states. In principle, we suppose, one could play chess by assuming that the opponent was an automaton with perfect automatic responses for all situations, but we doubt that anyone actually plays chess this way. An opponent with ToM is a far bigger challenge than a nodule of flint. But what about learning? Would it have been possible to learn Levallois reduction without a theory of mind?

The topic of learning occasionally arises in discussions of cognitive evolution, but almost always in the context of language. One of us (TW) has long argued that one learns tool use and tool making almost entirely through observation, repetition, and failure, and because of this, stone tools have few necessary implications for language (see, e.g., Wynn 1991). Others, such as Ambrose (2001), argue that this is too extreme a view and that language must have been involved in learning complex technologies such as hafting and Levallois. How does our cognitive account of Levallois bear on this disagreement? First, we confess to taking a conservative stance. We maintain that it is only possible to assess the minimum abilities required for a task and thus always risk underestimating abilities (Wynn 2002). Could the knapper of Marjorie's core have learned the significance and role of, say, the distal convexity without recourse to language? Would observation and practice have been sufficient? We believe that the answer is yes. If a teacher drew a novice's attention repeatedly to the distal convexity (by pointing, for example), this would have been enough. However, we believe that Levallois would have been very difficult to learn without some sort of guided attention; it probably required active instruction, and active instruction relies on joint attention and theory of mind. It does not require language.

The significance of our conclusion lies in its implication for cognitive evolution. Expert cognition has been in place for a long time. When a chess master plays a match or a blacksmith creates a fleur-de-lis, he or she relies primarily on a cognitive ability that evolved long before the advent of modern humans. It may seem counterintuitive to refer to one of our most valued abilities as archaic, but a moment's reflection should reassure even the more skeptical. Expertise takes years to acquire; it is not the result of flashes of insight but the result of dogged repetition and determination. Yes, the expert can access and use an appropriate solution almost instantly, but only because he or she has done the work necessary to encode more and more elaborate procedures into long-term memory. The flexibility results from long practice, not imagination.

Situating stone knapping in the cognitive domain of expertise, and LTWM, provides us with a cognitive framework for further comparison. The evolutionary shift from emphasis on *façonnage* to *débitage* is a long recognized watershed in technological evolution. How does it play out within the cognitive framework we have just established?

BIFACE REDUCTION

In Clive Gamble's brilliant 1999 book, *The Paleolithic Societies of Europe*, he emphasized the distinction between *façonnage* and *débitage* and suggested that the transition from the former to the latter marked a significant development. He is certainly not alone in holding this idea, as it reflects a generally held opinion among Paleolithic specialists. However, it has never been explicated in actual cognitive terms. The concepts of expertise, LTWM, and working memory should be powerful enough to enable us to detail just what, if anything, had evolved.

Unfortunately, there is no "Marjorie's core" of biface reduction. No one (to our knowledge) has written such a comprehensive description of a biface *chaîne opératoire*. This hampers comparison but does not cripple it. One practical problem, of course, is that few Acheulian sites have the resolution of Maastricht-Belvedere, and fewer have yielded debitage collections that can be refitted into coherent sequences of biface reduction. One of the few exceptions is Boxgrove, where several sets of debitage have yielded refits. One group in particular, from unit 4B, is especially informative(Roberts and Parfitt 1999).

The 4b scatter at Boxgrove represents the actions of a single knapper reducing a flint core into biface and, at the same time, producing useable flakes. The scatter includes 1,715 pieces larger than five millimeters in size, "thousands" between one and five millimeters, and a great deal of flint "dust." This scatter was very concentrated, covering only one quarter of a square meter. Roberts and colleagues were able to refit 132 of the flakes into twenty-eight groups. Most refit groups contained only a few flakes, but two were much larger, including twenty-one and twenty-four flakes, respectively. The first of these refit groups resulted from the knapper thinning a "break surface" on the core into a bifacial edge. The second resulted from a unifacial reduction of the same break surface, and although no connecting removals exist, it was probably part of the same sequence as the group of twenty-one. The flakes themselves are mostly very small, with only 7 percent over five millimeters in diameter, and only twelve over forty millimeters. They have a variety of dorsal scar patterns and a variety of butts, including plain, facetted, and crushed. All were flaked by a soft hammer.

Austin and colleagues (1999) have interpreted the 4b scatter as the debitage produced by a single knapper in a single sitting (literally!). He or she carried in a roughed-out core (none of the nodule reduction flakes are present) and reduced it into a handaxe. Both thinning and finishing flakes are present in the debitage. The knapper also was on the lookout for useable flakes. He or she selected the few larger thinning flakes and set them to the side (again, literally). After finishing the task the knapper carried away the resulting biface and a few of the larger flakes.

Unlike Marjorie's core, we have only a few flashes of the *chaîne opératoire*—enough to go on but not enough for comfort. The two larger refit groups yield a picture of two, perhaps only one, sequences of action. We cannot conclude that these were conceptually discrete constellations because the groupings result from the fortunes of refitting rather than the internally coherent steps of Marjorie's core reduction. Nevertheless, the groupings are not entirely mute. They do appear to have been linked to a local goal in the reduction procedure, the reduction of the "break surface." The knapping actions—platform preparation (e.g., crushing), striking thinning flakes, and striking finishing flakes—were directed to solve the knapping problem of the break surface (produced, Austin and colleagues [1999] believe, by end shock, a common problem at Boxgrove). These actions constitute a specific solution to one problem that emerged during the knapping of the biface, which was part of an overarching goal of biface and flake production.

How does this episode differ from Marjorie's core? First, the Boxgrove knapper had two goals operating in parallel—a handaxe and useable flakes (more on this later). Second, there was a hierarchy in the reduction task. Fixing the break surface was a set of knapping actions tied to a local goal, which was subsumed under the more inclusive goal of handaxe and flake production. But even though hierarchical in this sense, the whole enterprise was just not as tightly organized as Marjorie's core. The steps, to the degree that there were steps, were determined by local problems as they developed. The procedure was flexible in responding to problems but appears not to have been integrated into a set sequence of subroutines, as Marjorie's core most certainly was. Moreover, the Boxgrove knapper did a lot of knapping—thousands of blows apparently—in order to acquire a handaxe and a few flakes. This suggests a lot of ad hoc knapping in order to get to a recognizable result. The Marjorie's core knapper, on the other hand, was more deliberate, placing almost every blow to achieve maximum effect in completing the subroutine.

Expertise was certainly in play at Boxgrove, but it is not quite as impressive as that necessary for Marjorie's core. From the perspective of LTWM, the retrieval structure deployed for the handaxe is just not as complex as that underpinning Marjorie's core. Fewer specific cues were necessary and, perhaps more important, they were not organized into as many routines and subroutines. Cognitively, this simply means that the Boxgrove retrieval structure had fewer elements, took up less LTM, and took less time to learn than that of Marjorie's core. Our intent here is not to disparage biface *façonnage* or to imply that all biface *façonnage* was uniformly simple in a cognitive sense. Clearly, there were numerous technical developments over the temporal course of Acheulian *façonnage*—introduction of soft hammers, edge-preparation techniques that enabled invasive thinning flakes, and tranchet sharpening, to name just a few—all of which enabled flexibility and greater control over the final products. Many of these *façonnage* techniques came to play important roles in Levallois, which, as White and Ashton (2003) have noted, incorporates both *façonnage* and *débitage* elements. But we contend that even the finest biface *façonnage* falls short of the organizational complexity exhibited by Marjorie's core.

What about planning and working memory? It is here that our analysis yields a bit of a surprise. The knapper of Marjorie's core used a retrieval structure that enabled planning actions further into the future than that of biface reduction. This may have required a larger attention capacity than biface reduction, but it also possible that the retrieval structure itself was powerful enough that close attention was not often necessary. The surprising bit comes from the Boxgrove knapper. Biface reduction did not consume all of his or her working-memory capacity. There was enough attention available to monitor the process for useable flakes. The knapper had to hold in mind two separate goals, and this is a true working-memory task. But wait. Might not the knapper simply have sorted through the debitage heap after completing the task? This is possible, but recall that the flakes were set to the side, suggesting that they were identified and moved as they were produced.

We are left with a slightly unexpected result. Yes, the Levallois retrieval structure was (and is) more complex than that of biface reduction and required more resources of long-term procedural memory. Moreover, deploying this retrieval structure required more working memory than simple biface reduction. So Gamble's suspicions were on target. However, the biface knapper at

Boxgrove was able to make a handaxe and look out for useable flakes at the same time. We have no evidence for a parallel procedure with Marjorie's core.

CONCLUSION

Our analysis of Marjorie's core and comparison to Boxgrove biface *façonnage* supports two conclusions. First, the cognitive style that psychologists term "expertise" is easily able to encompass modern craft production such as blacksmithing, and also prehistoric craft production, including stone knapping. As a cognitive strategy, expertise is based on the ability to rapidly access well-learned patterns, knowledge, and procedures that have been stored in long-term memory over the course of years' practice. This style of thinking is largely nonverbal. In modern craft production, verbal declarative knowledge is a component of retrieval structures, but it is not central to, or perhaps even necessary for, expert performance. Verbal instruction may streamline learning, but it is not necessary for deploying the retrieval structures themselves. Here is a style of thinking that is responsible for many of our most impressive modern accomplishments, but it is not dependent on language.

Second, the power of expert retrieval structures has evolved over the course of hominin evolution. The knapper of Marjorie's core deployed a retrieval structure that was more complex, with greater inherent flexibility, than that demonstrated by the Boxgrove knapper. If this contrast is typical, then something had evolved in the 300,000 years separating the two events. It could have been something as simple as long-term-memory capacity (for retaining a larger number of alternative routines) or could have related to speed of access, or even working-memory capacity (amount of information held in attention and processed). But the style of thinking had not itself changed. Indeed it is with us still and remains an important element of modern cognition.

Could the cognitive model of expertise and retrieval structures in particular provide the basis for a more general approach to evaluating and comparing Paleolithic technical performances? In principle the answer is clearly yes; but there are serious practical roadblocks. There is, for example, no uniform, generally agreed-upon technique for describing and/or quantifying *chaînes opératoires*. Without such a standard vehicle, every attempt at comparison must begin with a redescription of each example. Recently, Miriam Haidle (2009) developed a standard vehicle she terms a "cognigram" and has used it to compare the tool use of nonhumans and early hominins. It is a promising start, but it will only be effective if other archaeologists are willing to use it. Until then, cognitive comparisons will be limited to a few cases at a time. But even such limited comparisons could begin to contrast the retrieval structures deployed in stone knapping at a variety of points in hominin evolution.

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SIX

On Standardization in the Paleolithic

Measures, Causes, and Interpretations of Metric Similarity in Stone Tools

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ABSTRACT

Questions of morphological standardization in Paleolithic stone tools have important implications for the cognitive and technological capacities of early hominins. Past treatments of the topic suffer from an inadequate definition of the concept of "standardization" and a scarcity of quantitative comparisons of morphological variation. Ranges of variation in the sizes and shapes of Middle and Lower Paleolithic artifacts from several sites are compared using a bootstrapping method. These comparisons illustrate how variables related to the basic technological constraints of working isotropic stone and the fracture qualities of particular raw materials may lead to the appearance of differential standardization. Because they are influenced by so many factors, artifact forms may be less informative about technological "design" among ancient hominins than are phenomena such as core reduction and raw material exploitation.

INTRODUCTION

The potential for "standardization" in the shapes of Paleolithic artifacts, with its many implications for the cognitive and linguistic capacities of early hominids, has excited much discussion among paleoanthropologists. Considerations of artifact standardization fall into two main groups: those focusing on final forms of artifacts (morphological standardization), and those concentrating on techniques and methods of production (procedural standardization). Some authors assert that a high degree of morphological similarity among certain early Paleolithic artifacts—Acheulian bifaces in particular—demonstrates the existence of culturally, perhaps even symbolically transmitted "norms" of artifact design (Gowlett 1984, 1987; Hopkinson and White 2005; Wynn 1985, 1995). These assertions in turn have been challenged at both the observational and the interpretive levels (e.g., Chase 1991; Davidson and Noble 1993; Dibble 1989; Noble and Davidson 1996). Other authors have asserted that Upper Paleolithic stone stool industries show greater levels of morphological standardization than earlier ones as a function of increasingly rigid symbolically encoded constraints on "intended" artifact morphology (Mellars 1995:381–382); again, the assertion has been challenged at the empirical level (Marks, Hietala, and Williams 2001; Monnier 2005). Various authors have proposed that the wholesale adoption of prismatic blade production and microlithic technologies in the early Upper and late Paleolithic, respectively, occurred as a response to increasing use of composite tools and the concomitant requirements for dimensionally standardized inserts (Bar-Yosef and Kuhn 1999; Fisher 2006; Hayden and Gargett 1988). On the procedural side, many researchers argue that the repetitive, stereotypical sets of technological actions manifest in reconstructed lithic core reduction sequences or *chaînes opératoires* are evidence for culturally prescribed, perhaps symbolically encoded plans for action in the production of tools (e.g., Boëda 1990, 1991; Gowlett 1996; Karlin and Julien 1994; Roche et al. 1987; Schlanger 1994).

Procedural and morphological standardization can be demonstrated in the technological productions of recent humans, and they could be significant signposts in the evolution of human cognition. However, there are substantial shortcomings in the ways "standardization" as an empirical phenomenon is conceptualized and measured. This chapter examines critically two features of arguments, pro and con, about morphological standardization in stone tools. The first is the definition of the concept of standardization itself, a definition that conflates observations about morphological variation—or its absence—with inferences about the ultimate cause of that variation. A whole range of factors beyond human choice can serve to attenuate or expand ranges of variation in artifact form. The second relates to the ways morphological variation among artifact classes or samples is assessed. Many assertions about differing levels of standardization are non-quantitative and most are non-probabilistic. A probabilistic method for comparing the most common measure of standardization, the coefficient of variation (CV), is applied to a series of Middle and Lower Paleolithic data sets in order to examine how a range of factors influence levels of variation in the sizes and shapes of stone artifacts.

QUESTIONS OF STANDARDIZATION IN THE LOWER AND MIDDLE PALEOLITHIC

Statements about the relative degree of (or absence of) standardization in early stone technologies are common to the point of being routine. For example, Mellars (1989, 1991, 1995) has long argued that Upper Paleolithic stone tools show evidence of "a much more standardized, categorical way of conceptualizing tool forms," which can be contrasted with the "much looser and ill-defined forms of most Lower and Middle Paleolithic tools" (Mellars 1995:90; see also Mellars 1989; Otte 1990). These differences he attributes at least in part to a more fully developed form of cognition among Upper Paleolithic hominins. Whereas Mellars's general assessment fits well with the "received view" of Upper Paleolithic technological variation (summarized in Sackett 1988:416–417), some researchers disagree, arguing that the apparent standardization of Upper Paleolithic tools is itself an artifact of the typology used to classify them (Clark and Willermet 1995) or that the case for standardization in later time ranges has simply been overstated (Sackett 1988:418). Moreover, attempts to put Mellars's assertion to the test using Paleolithic assemblages from Europe, the Levant, and North Africa have failed to identify evidence for greater standardization of tool blanks or debitage in the Upper Paleolithic (Chazan 1995:753–756; Marks, Hietala, and Williams 2001; Monnier 2005), although Marks and colleagues (2001) note that this may be as much a function of the specific variables chosen for study as it is a reflection of past behavioral tendencies.

Arguably the strongest, and certainly the most widely discussed, case for arbitrarily imposed forms in early stone tools concerns bifacially flaked handaxes in Acheulian assemblages. Many authors have remarked at the apparent uniformity of Acheulian bifaces across the globe (e.g., G. Clark 1971:39–40; J. D. Clark 1994; Schick and Toth 1993; Wynn 1995). Gowlett (1984, 1996) has made the most explicit statements about standardization early in human prehistory and is also one of the few scholars to actually present data showing the extent of variation/similarity in the shapes of these artifacts. Working initially with Acheulian assemblages from East African sites such as Kilombe, Gowlett is able to demonstrate a high degree of homogeneity in the general shapes of Acheulian handaxes, as measured by the correlations among linear dimensions as well as by variation in ratios of length/width and width/thickness (Gowlett 1984). The remarkable regularity of handaxe forms at Kilombe and other sites, he argues, "shows a high degree of standardization, and must imply a well-developed mental image of the desired end-product" (Gowlett 1984:185; see also J. D. Clark 1994:453–454). More recently, Sharon (2009) has made very similar assertions about the dimensions of large Acheulian cleaver flakes. Although the measurements of handaxes from Kilombe do appear to show great morphological uniformity, Gowlett does not demonstrate that the handaxes resemble one another more than members of other artifact classes, only that they fall into one basic cluster.

Gowlett's observations have provided much fodder for discussion. Davidson and Noble (1993) observe that bifaces from European Acheulian sites show strikingly similar proportions to those from East Africa. They conclude that uniformity over such vast ranges of time and space cannot reflect a single system of cultural transmission and should have more to do with technological constraints on bifacial reduction or the ways in which classes such as "handaxe" are defined (Davidson and Noble 1993:371–372). Elsewhere (Noble and Davidson 1996:196–198) these same authors argue that the forms of handaxes recovered by archaeologists were simply the by-products of resharpening large cutting tools or exploitation of bifaces as flake cores and thus should not even be considered "designs" in the conventional sense (cf. Dibble 1989; Sinclair and McNabb 2005:186).

Thomas Wynn has written more extensively about the cognitive implications of Acheulian tool kits than any other author (Wynn 1979, 1985, 1989, 1995) and has most squarely faced the paradoxical aspects of these artifacts. Wynn adopts a position intermediate between that of Gowlett and that of Davidson and Noble. He (Wynn 1998:80–81) agrees with Gowlett that "handaxes were standardized tools, in that *Homo erectus* manufactured a single basic shape for thousands of generations" and that such repetitive behavior implies the existence and transmission of "some kind of community norm." At the same time, he recognizes that the persistence of tool forms over thousands of generations shows that these "community norms" were a fundamentally different order of culture construct from the kinds of design conventions with which most anthropologists are familiar (Wynn 1998:80–81; see also Hopkinson and White 2005; Jelinek 1977:15; Schick and Toth 1993:280–283).

STANDARDIZATION AND REDUNDANCY

Although many authors have discussed the behavioral and cognitive significance of standardization in Paleolithic stone tools, few have hazarded an explicit definition of the term. *The New Shorter Oxford English Dictionary* (1993) defines the verb "to standardize" as "[to] cause to conform to a standard or uniform size, strength, form, etc." This definition corresponds well with everyday usage. Key to the definition is the word "cause," which implies the active imposition of observed characteristics by the manufacturer of an artifact. Standardization implies not only morphological homogeneity but also the active application of norms in achieving that homogeneity. In other words, standardization is not a property of objects but an inferred characteristic of the behavior of the makers of those objects.

For a researcher working with living peoples, the act of applying standards can be observed, documented, inquired about, and critically assessed. This, of course, is impossible for the prehistorian. In fact, for the Paleolithic archaeologist or anyone else working with past societies that did not leave a written record, the only empirical evidence of standardization is morphological redundancy. The facts that alert an observer to the potential existence of standardized artifact forms consist of nothing more than an especially high degree of homogeneity within a class of artifacts. Ideally, individual members of an hypothetical "standardized" class should (1) be more alike than physical and mechanical factors dictate, and (2) be more alike than members of other, supposedly non-standardized artifact classes defined at a comparable level of specificity.

For many archaeological applications the distinction between standardization and uniformity may seem inconsequential. Researchers concerned with comparatively recent periods are probably safe in assuming that some kinds of design standards existed and that these can be discovered through inspection of morphological variation in artifacts. When investigating early Paleolithic technologies, the inference of agency based on simple morphological redundancy is more problematic. The questions being asked about Mousterian and Acheulian stone artifacts concern whether arbitrary norms in the design and manufacture of artifacts even existed. To accept a high degree of formal redundancy as prima facie evidence for rigid standards of design is to presume at the outset exactly what one is setting out to investigate.

The reliability of conclusions about the existence of norms of design based on artifact morphology also rests on the assumption that morphological redundancy can only reflect decisions made by ancient tool makers. However, a range of proximate factors having little to do with human agency can influence levels of morphological redundancy among objects (e.g., see Chase 1991:206–207). The mechanics of stone fracture, the effects of differential reduction, and the effects of raw material sizes and qualities all have particular relevance to Paleolithic stone tools.[1]

At least two generations of experimental study have shown how, all other things being equal, application of a given degree of force to a platform on a core with a particular morphology will result in the detachment of flakes of more or less predictable size and shape (Cotterell and Kamminga 1987; Dibble and Pelcin 1995; Pelcin 1997; Speth 1972, 1974, 1975; Young and Bonnichsen 1984). Conversely, factors such as the force of the blow and the angle of detachment must be held within relatively narrow tolerances if one is to successfully produce a flake of useful size and shape.[2] The fact that basic technical processes such as bifacial shaping and prismatic blade manufacture have been reinvented repeatedly throughout prehistory and across the globe attests to the basic mechanical limitations on methods of stone flaking. There is more than one way to skin a core, but because of the ways isotropic, brittle materials fracture, there is not an infinite number of ways. These simple mechanical facts must introduce a level of morphological redundancy into the products of stone flaking.

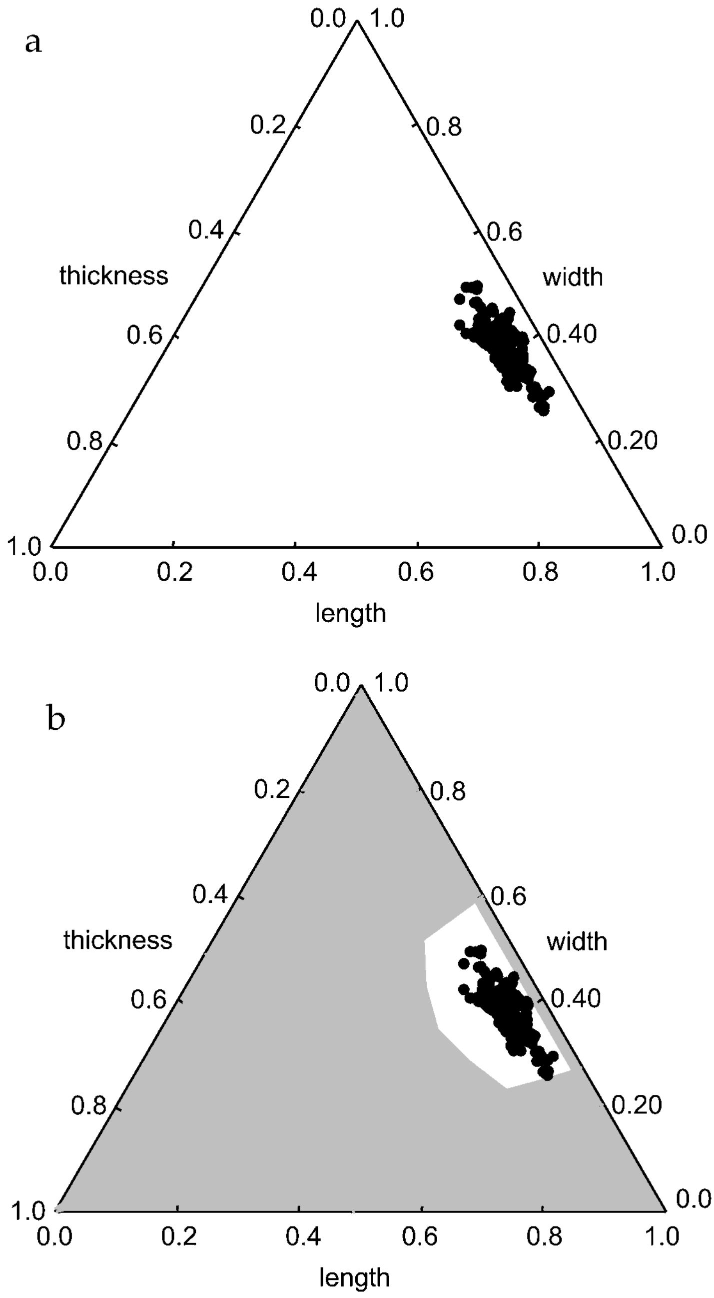
The "standardizing" effects of stone fracture mechanics are especially important to discussions about the morphological regularity of Acheulian bifaces. To a certain extent, the similarities among handaxes stem from the definition of the category itself. Artifacts that fall outside the range of typologically acceptable forms for handaxes will be assigned to different classes (discs, cores, cleavers, etc.) (Dibble 1989); in this case, the imposition of form comes from the archaeologist, not the tool maker.[3] The geometry of biface technology is also strongly constrained by fracture mechanics. Make a biface too thick or too thin, the edges too obtuse or too acute, and it will be impossible to successfully thin the artifact, produce a useful cutting edge, or even detach a flake (see Callahan 1979; Whittaker 1994:185–199; Young and Bonnichsen 1984). In other words, it is practically impossible to produce an artifact by successful bifacial reduction that does not exhibit a certain range of morphological properties.[4] Longitudinal and transverse cross-sectional morphology are probably most strongly constrained by the mechanics of bifacial reduction. Interestingly, the handaxes from Kilombe discussed by Gowlett appear substantially more standardized in shape ratios (coefficients of variation between 0.08 and 0.125) than in length or width (CVs between 0.15 and 0.30).

Technological constraints on artifact form do not just affect handaxes. What has just been asserted for biface technology is also true of Levallois, prismatic blade technology, or the various prepared core techniques common in the Lower and Middle Stone Ages of Africa. The mechanics of stone fracture force the tool maker down certain pathways (e.g., Brantingham and Kuhn 2001). If tolerances are exceeded, the results will not only look bad but will probably be wasteful or even useless. Just as importantly, they are likely to be excluded by archaeologists from the very artifact classes about which arguments for standardization are made.

The combination of mechanical limitations and imposed typological conventions may constrain artifact morphological variability, simulating imposed standardization. This can be illustrated using a sample of 100 whole Levallois flakes from Units I and II of Jelinek's excavations at Tabun cave (Jelinek 1981, 1982). Figure 6.1a shows the 100 specimens plotted on a tripole graph according to three linear dimensions; the use of the tripole here follows Van Peer (1992). The points form a tight cluster strongly along the right-hand edge of the graph. This clustering might lead to an inference that Levallois flakes were produced according to a standardized model. On closer inspection, however, it is clear that the appearance of clustering is in large part illusory: a great deal of the empty area on the graph actually represents artifacts that either could not physically exist or that would never be classified as Levallois flakes, regardless of how they were produced.

For example, we can assume that flakes in which thickness was less than one-twelfth of any linear dimension, or length more than six times width, would be unlikely to survive in complete, measurable condition. Moreover, specimens for which thickness was greater than length or width would not even have been identified as flakes. We can further assume that an artifact would not be classified as a Levallois flake if its length were less than 75 percent of its width or if thickness were more than one-third of either length or width; in all likelihood, this is a very generous definition. By that same token, we know that specimens whose length was more than 2.5 times width were classed as blades in this database. In Figure 6.1b, the areas of the graph excluded for these technical, physical, or definitional reasons are shaded; the residual variable space containing all *possible* Levallois flakes is shown as the unshaded area. In the second figure the free variable space is much smaller, the Levallois flakes take up much more of it, and as a consequence they appear much less "standardized" than before. All that can be said for certain is that the Levallois flakes are relatively thin (part of the standard definition of this class of artifact) and that they are not very elongated (probably a function of the sample definition).

Another factor that could lead to differential levels of redundancy in the shapes and sizes of Paleolithic tools are variable artifact life histories. The potential consequences of progressive tool reduction through resharpening have been brought to the attention of Paleolithic archaeologists largely through the efforts of Dibble (1987, 1995) and others (Hiscock 1996; Holdaway, McPherron, and Roth 1996; Kuhn 1992; McPherron 1994). Because material is removed each time a tool or core is exploited, reworked, or sharpened, the sizes and shapes of artifacts change over their use lives. Varying degrees of reduction can be expected to result in varying degrees of redundancy in both the sizes and shapes of stone



6.1. Triangular graphs showing average dimensions of Levallois flakes from Tabun cave. Shaded area represents variable space excluded because of typological or mechanical constraints.

tools. As tools or cores are reworked and reused, they eventually reach a size threshold beyond which they no longer function. Hypothetically, assemblages in which all artifacts are reduced to the smallest useable size should exhibit a greater degree of dimensional redundancy than assemblages in which artifacts were abandoned at varying stages of reduction. If implements undergo a regular set of morphological transformations as they are reduced (Dibble 1987, 1995; McPherron 1994), then a high degree of metric redundancy could also result from a uniform level of reduction. Influences on levels of artifact reduction are many. The costs of procuring raw materials is the most often-cited factor, but varying degrees of mobility and the type and duration of activities can also play important roles (Andrefsky 1994; Hayden 1977; Kuhn 1991, 2004).

The physical characteristics of different lithic raw materials constitute a third set of proximate influences on degrees of dimensional and morphological redundancy in stone tools. The dimensions of nodules in which raw materials occur set upper limits on the sizes of cores and tools. All other things being equal, we might expect samples of artifacts made from especially small nodules of raw material to exhibit relatively small ranges of metric variation. Preferential fracture or cleavage planes, such as are frequently observed in vein quartz or slate, could easily contribute to unusual regularity in artifact forms.

Clearly, all of the phenomena discussed above have interesting behavioral and cognitive implications of their own. Technological acts solve problems. The choice of one specific method of blank production, the decision to resharpen or to abandon a tool, or the selection of one material as opposed to another may be highly significant in investigating past behavior and cognition. The point is that many of the choices made by ancient tool makers could have profound consequences for the relative degrees of homogeneity in the shapes or sizes of artifacts, without any intention to achieve dimensional or morphological standardization. In these cases, the appearance of "standardization" is merely a by-product of other actions or conditions.

ASSESSING AND COMPARING MORPHOLOGICAL REDUNDANCY

Previous critiques of interpretations of Paleolithic artifact standardization (e.g., Chase 1991; Davidson and Noble 1993; Dibble 1989) have cited many or all of the factors discussed above as possible explanations for high degrees of uniformity in ancient stone tools. By and large, however, past treatments have been limited to observations that raw material, technology, or reduction *could* act to constrain ranges of variation in artifact form. Explicit demonstrations of such effects are largely lacking. The next obvious step is to examine whether, and to what degree, raw material, reduction, or the mechanical constraints of stone fracture have quantifiable effects on the appearance of standardization in archaeological artifacts. Doing so requires some means for assessing and comparing levels of variation or uniformity.

Statements about standardization are at least pseudo-quantitative and should be treated as such. Wynn's (1989:3–4) argument against the relevance of quantitative approaches is hence rather puzzling. Focusing only on those artifacts that most clearly show evidence for a certain type of behavior or hypothetical conceptual schemata exposes one to the risk—to paraphrase a common metaphor—of concluding that at least some monkeys really are capable of writing the works of Shakespeare when given enough time at a typewriter. To assert that a group of artifacts exhibits a remarkable uniformity and that this uniformity bespeaks application of criteria of design, one should be able to demonstrate that levels of uniformity are in fact remarkable.

The measure of variation most often used for comparing metric attributes across artifact classes is the coefficient of variation (CV), calculated by dividing the standard deviation of a sample of observations by the mean. The principal advantage of this measure is that it is dimensionless, expressing the standard deviation as a proportion of the mean. However, there is always uncertainty involved in estimating population parameters from sample means and standard deviations, and it is insufficient to simply compare CV values among samples: even samples from the same population are unlikely to have identical CV values, especially when the samples are small. What is needed is a method for assessing the likelihood that two calculated CV values come from populations with identical levels of variation.

One common approach to comparing CV values probabilistically is through confidence intervals. The confidence interval uses sample statistics to estimate the likely range for the population statistic. For example, a 95 percent confidence interval about a sample CV value marks the range that we are 95 percent certain contains the CV value for the population from which the sample is drawn. This estimated range serves as a basis for comparing sample values. (Eerkens and Bettinger [2001] propose an alternative approach to comparing CV values, not covered here.)

The conventional approach to estimating confidence intervals for the CV is based on the F-ratio. However, the approach assumes that the population is normally distributed, and violation of normality assumptions can result in intervals that are much too narrow or too wide (Kavamme, Stark, and Longacre 1996:117, 120). The alternative used in this study involves the technique known as bootstrapping or resampling. The resampling method assumes only that the sample observations are fairly representative of the population distribution, normal or not. In order to estimate a particular parameter, a large number of "pseudo-samples" of the same size as the original are selected randomly, with replacement, from the original sample. Because sampling with replacement is used, the pseudo-samples are not necessarily identical with the original. Composite statistics for a large number of pseudo-samples are then used to estimate the population parameter.

The procedure used here was as follows: for each measurement or index on each artifact sample, a pseudo-sample of equal size to the original was selected randomly (with replacement) from the original sample distribution, and the coefficient of variation calculated. This procedure was repeated 10,000 times. The fifth and ninety-fifth percentiles of the resulting set of 10,000 CV values were then calculated. These serve as the upper and lower confidence intervals for the CV of a particular measurement and artifact sample.[5] The fact that most confidence intervals shown below are asymmetrical is a function of the sample distributions themselves.

The graphs that follow are similar in format. Black dots mark the sample coefficients of variation for each sample, so that the overall level of variation within the sample can be assessed in terms of the dot's position on the y-axis. The linear tails mark the upper and lower limits of the bootstrapped 95 percent confidence intervals about the sample CV. Assessment of the level of similarity/difference between sample values is based on the degree of overlap between the confidence intervals. Here we are testing the null hypothesis that two samples came from populations with identical values of the CV. If the 95 percent confidence intervals about a particular statistic in two samples do not overlap, we are safe in assuming that the samples came from populations with different values for that statistic. However, complete non-overlap is an overly stringent criterion. A common rule of thumb is that if the confidence interval for either sample contains the target sample statistic for the other, the null hypothesis cannot be rejected. Likewise, if target statistics for both samples lie outside the other sample's 95 percent confidence intervals, the null hypothesis can be rejected with a reasonable degree of certainty.

TESTING FOR ALTERNATIVE CAUSES OF APPARENT STANDARDIZATION

The analyses below examine whether a series of factors, all completely independent of the application of formal design standards, can actually have detectable effects on the appearance of standardization in particular artifact classes. Data are measurements of retouched tools and cores from Middle and late Lower Paleolithic sites from around the Mediterranean basin (Italy, Turkey, and Israel), dating to between roughly 300,000 and 45,000 BP. The various sites and artifact classes offer a variety of opportunities for comparison in which factors such as raw material properties and technology of production can be controlled. All of the assemblages employed were probably produced by late archaic members of the genus *Homo* (Neandertals and *Homo heidelbergensis*). Brief descriptions of the sites and assemblages used appear below, and key data are summarized in Table 6.1.

Riparo Mochi is one of the important group of Paleolithic cave and rock-shelter sites sometimes called the Grimaldi caves, located in Italian Liguria a short distance from the French/Italian border. The Mousterian strata, more than four meters thick, were excavated in arbitrary ten-centimeter levels during the 1940s and 1950s. No absolute dates are available for the Mousterian layers at Riparo Mochi, although the most recent Mousterian deposits have been attributed to the latter part of the "Würm II" or MIS 3 (de Lumley-Woodyear 1969) and are probably roughly coeval with the sequence at Grotta di Sant'Agostino (below). Each of the two samples used in this study derives from a series of cuts spanning a depth of approximately 1.5 meters. Raw materials include several varieties of flint, limestone, silicified limestone, and fine-grained quartzite, most of which could be obtained locally in the form of beach cobbles.

Grotta di Sant'Agostino is a large, open cave located on the central Tyrrhenian (western) coast of Italy a short distance north of the town of Gaeta. The site was excavated in 1948 by E. Tongiorgi, who divided the sandy matrix into five layers (A0–A4) (Tozzi 1970). The Mousterian of Sant'Agostino is notable for the small sizes of the artifacts (which seldom exceed 3.5 centimeters in length), attributable to the local raw materials, which consist of diminutive flint pebbles found in widely scattered fossil beach deposits. Layers A1–A3 at Sant'Agostino have yielded a series of ESR (Electron Spin Resonance) dates ranging from 45,000 to 54,000 BP (Schwarcz et al. 1990–1991; Kuhn 1995a:table 3.8). For the analyses below, the sample has been divided into two parts, one containing materials derived from layer 1 and the other combining materials from layers 2–4.

Tabun cave, located in the Wadi Mughara on the western face of Mt. Carmel, Israel, is one of the best-known Paleolithic sites in the world, preserving a record of hominid activities stretching from the Acheulian through the late Mousterian. Tabun was first excavated by Prof. D. Garrod between 1929 and 1934 (Garrod and Bate 1937). The samples used here come from Jelinek's meticulous re-excavation of the site (1967–1972) (Jelinek 1981, 1982). The artifact samples

Table 6.1. Sites and samples used in analyses.

Site/assemblage	*Artifact class*	*Dimension*	*Lower confidence interval*	*Coefficient of variation*	*Upper confidence interval*
GROTTA DI SANT'AGOSTINO					
Level 1	scrapers	length	0.195	0.215	0.236
		width	0.195	0.227	0.255
		l/w ratio	0.231	0.255	0.276
		w/th ratio	0.342	0.387	0.429
	cores	length	0.128	0.154	0.173
		width	0.108	0.129	0.145
		l/w ratio	0.088	0.106	0.119
		w/th ratio	0.190	0.251	0.301
Levels 2–4	scrapers	length	0.195	0.229	0.260
		width	0.172	0.198	0.219
		l/w ratio	0.224	0.268	0.306
		w/th ratio	0.242	0.275	0.305
	flakes	length	0.235	0.273	0.307
		l/w ratio	0.314	0.371	0.421
	cores	length	0.109	0.148	0.178
		width	0.118	0.184	0.232
		l/w ratio	0.079	0.146	0.200
		w/th ratio	0.226	0.277	0.315
RIPARO MOCHI					
Cuts 30–46	scrapers	length	0.185	0.209	0.263
		width	0.234	0.305	0.355
		l/w ratio	0.295	0.385	0.449
		w/th ratio	0.251	0.342	0.403
	flakes	length	0.292	0.313	0.334
		l/w ratio	0.372	0.394	0.415
	cores	length	0.178	0.241	0.292
		width	0.199	0.263	0.309
		l/w ratio	0.106	0.150	0.178
		w/th ratio	0.215	0.274	0.316
Cuts 56–70	scrapers	length	0.171	0.280	0.340
		width	0.203	0.270	0.318
		l/w ratio	0.225	0.320	0.380
		w/th ratio	0.211	0.285	0.341
	flakes	length	0.329	0.352	0.374
		l/w ratio	0.386	0.415	0.444
TABUN CAVE					
Bed 72I	scrapers	length	0.130	0.164	0.187
		width	0.163	0.215	0.248
		l/w ratio	0.170	0.240	0.287
		w/th ratio	0.244	0.333	0.396
	bifaces	length	0.129	0.181	0.221
		l/w ratio	0.084	0.151	0.187
		w/th ratio	0.139	0.199	0.233

continued on next page

Table 6.1—*continued*

Site/assemblage	*Artifact class*	*Dimension*	*Lower confidence interval*	*Coefficient of variation*	*Upper confidence interval*
Bed 73S	scrapers	length	0.132	0.185	0.227
		width	0.168	0.225	0.268
		l/w ratio	0.251	0.315	0.356
		w/th ratio	0.279	0.355	0.403
	bifaces	length	0.144	0.280	0.337
		l/w ratio	0.099	0.188	0.251
		w/th ratio	0.121	0.174	0.214
Bed 74S	scrapers	length	0.157	0.207	0.252
		width	0.218	0.263	0.303
		l/w ratio	0.192	0.317	0.414
		w/th ratio	0.293	0.353	0.402
	bifaces	length	0.160	0.198	0.229
		l/w ratio	0.100	0.120	0.136
		w/th ratio	0.198	0.255	0.296
YARÝMBURGAZ CAVE					
	quartz flake tools	length	0.206	0.532	0.639
		l/w ratio	0.136	0.193	0.232
		w/th ratio	0.178	0.267	0.332
	flint flake tools	length	0.297	0.327	0.353
		l/w ratio	0.310	0.341	0.370
		w/th ratio	0.304	0.380	0.460

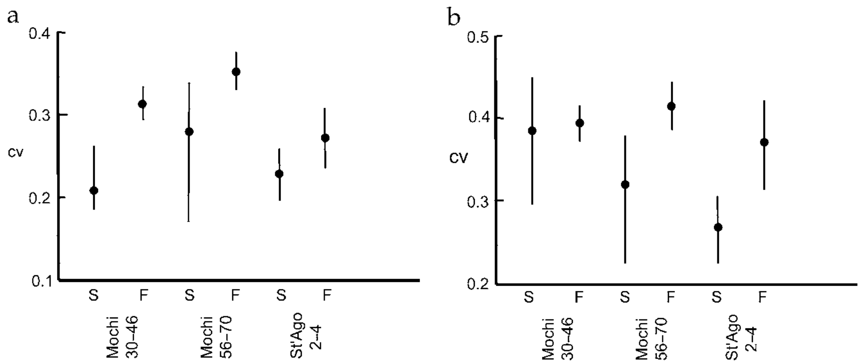
used here come from beds 72I, 73S, and 74S of Jelinek's excavations. Bed 72I marks the bottom of Jelinek's unit X, considered to be transitional between the Mugharan tradition and the early Levantine Mousterian of unit IX. Beds 73S and 74S come from the top of unit XI and are the uppermost Yabrudian layers at the site: they fall within Garrod's unit Ea. Five thermoluminescence dates from bed 73 average about 294 kya BP, with a range of between 265 ± 31 ka and 335 ± 39 ka BP (Mercier et al. 1995:503). Large packages of high-quality flint appear to have been available in the vicinity of Wadi Mughara and Tabun cave throughout the site's long occupational history.

Yarimburgaz cave is situated in eastern Thrace (European Turkey) near the northern shore of the Marmara Sea (Kuhn, Arsebük, and Howell 1996). Sediments within the lower chamber at Yarimburgaz cave have been divided into three main sedimentary cycles (Farrand and McMahon 1997); more than 90 percent of the artifacts are derived from layers W and X in cycle 3 (the most recent). The lithic assemblage consists mainly of flake tools with irregular edges, along with a variety of core forms, and fits within that group of Middle Pleistocene assemblages without bifaces sometimes called Tayacian. The precise age of the occupation of Yarimburgaz cave remains uncertain. A series of ESR dates on bear teeth range from oxygen isotope stage 6 back through stage 8 (Blackwell et al. 1990). Paleontological evidence suggests that the archaeological deposits at the site date to the later half of the Middle Pleistocene; thus, the Yarimburgaz assemblage is probably roughly the same age as or somewhat more recent than the sample from Tabun beds 72–74. Raw materials include flint, quartz, and quartzite obtained in the form of large, rounded cobbles.

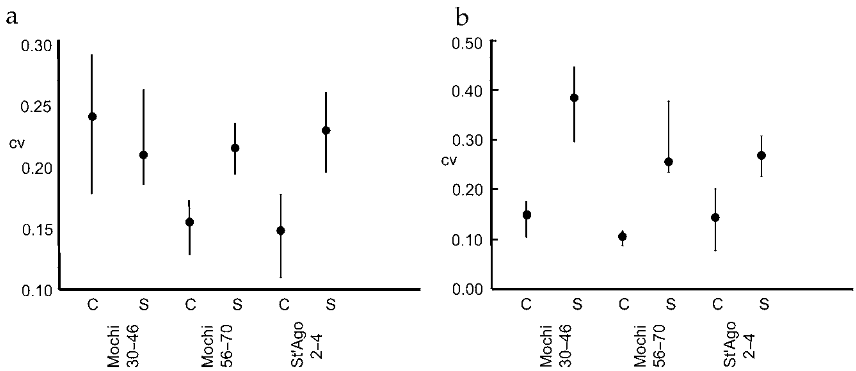
Most of the analyses below are based on comparisons of four basic classes of stone artifact: unretouched flakes, simple sidescrapers, bifacial handaxes, and unifacial disc (centripetal) cores. Only measurements of unbroken specimens are used. All relevant assemblages are included except where available data are biased by selective sampling procedures or where samples of unbroken artifacts are too small for reliable comparisons. Measurements of flakes and flake tools include technical length, midpoint width, and midpoint thickness (following Fish 1979:30). For bifaces, overall length, maximum width, and midpoint thickness are the measures used (see Rollefson 1978:41, for definition of measurements). Two ratios, length/width (length / maximum width in the case of bifaces) and width/thickness, are employed as measures of an artifact's "shape" or proportion. Obviously, many more sophisticated assessments of artifact form could and have been devised, but these two ratios are widely employed in lithic analysis. All measurements were made by the author except for those of bifaces from Tabun cave, which are taken from Rollefson (1978). Rollefson's data were employed because the Tabun collections are currently split between Israel and the United States, and many of the bifaces from Jelinek's excavations were not easily accessible. As these are the only bifaces employed, interindividual differences in measurement techniques should not affect results.

TECHNOLOGICAL CONSTRAINTS 1: COMPARISON OF MOUSTERIAN FLAKES, SCRAPERS, AND CORES

Comparisons of flakes, simple sidescrapers, and cores from two of the Mousterian sites, Grotta di Sant'Agostino and Riparo Mochi, yield what are perhaps the most telling examples of different causes for apparent standardization. Table 6.2 and Figures 6.2a and 6.2b show confidence intervals about the coefficients of variation for lengths and length/width ratios of unmodified flakes and simple sidescrapers from the two sites. Not surprisingly, sizes and shapes of retouched tools tend to be more redundant—that is, they possess smaller coefficients of variation—than sizes and shapes of unmodified flakes, although the differences are not always statistically significant. Apparently, the selection of blanks for retouch tools and/or retouch and reduction resulted in the scrapers having



*6.2. Confidence intervals (95 percent) about (*a*) coefficients of variation of lengths and (*b*) length/width ratios for flakes and sidescrapers from Riparo Mochi and Grotta di Sant'Agostino.* F *indicates flakes;* S *indicates sidescrapers.*



*6.3. Confidence intervals (95 percent) about (*a*) coefficients of variation of lengths and (*b*) length/width ratios for sidescrapers and unifacial centripetal cores from Riparo Mochi and Grotta di Sant'Agostino.* S *indicates sidescrapers;* C *indicates cores.*

more uniform sizes than unmodified flakes. More surprising are results shown in Figures 6.3a and 6.3b, which compare retouched tools and unifacial, centripetally worked cores. In two of the samples, sizes of cores show significantly less variation in overall size. In all samples, the shapes of cores (length/width ratios) have significantly lower coefficients of variation than those of sidescrapers. By conventional criteria, cores appear to be the most highly "standardized" artifact class of all; in fact, CV values for length/width ratios of cores are on the low end for values reported for Great Basin projectile points and northern European microliths (Eerkens and Bettinger 2001:499).

Table 6.2. Coefficients of variation and bootstrapped confidence intervals for measures of lithic artifacts used in Figures 6.2 through 6.5.

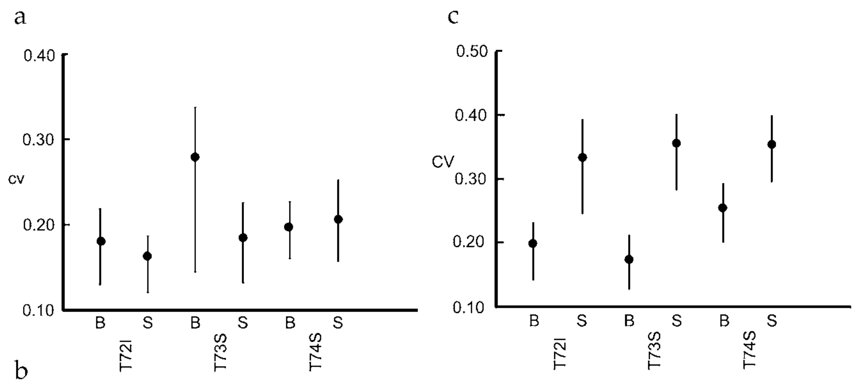
Site	*Level or layer*	*Culture complex*	*Approximate age*	*References*
Riparo Mochi	cuts 30–46	Middle Paleolithic	Upper Pleistocene	de Lumley-Woodyear 1969; Kuhn 2004
	cuts 56–70	Middle Paleolithic	Upper Pleistocene	
Grotta di Sant'Agostino	level 1	Middle Paleolithic	43,000 ± 9000	Tozzi 1970; Kuhn 1995b
	levels 2–4	Middle Paleolithic	53,000 ± 7000; 54,000± 11,000	
Yarýmburgaz cave	entire assemblage	Lower Paleolithic "Tayacian"	late Middle Pleistocene	Kuhn et al. 1996
Tabun cave	bed 72I	"transitional"	< 265,000 BP	Jelinek 1981, 1982
	bed 73S; bed 74S	Yabrudian	265,000 ± 31,000 BP to 335,000 ± 39,000 BP	Mercier et al. 1995

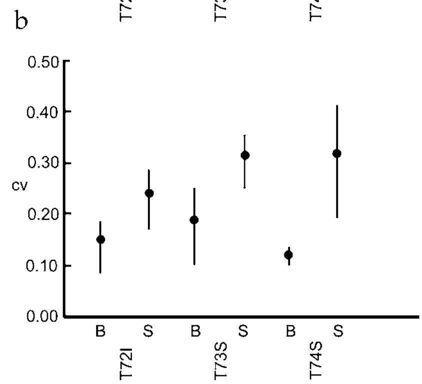
From this comparison it can be observed that levels of morphological redundancy run counter to normal expectations. Few would argue that Mousterian tool makers were aiming to create residual cores of a particular size and shape, and yet cores are the most morphologically redundant artifacts. The similarity among the cores is not a function of how artifacts were classified. Neither size nor length/width ratios were part of the definition of unifacial centripetal cores; the class was defined solely on the basis of the orientations and distributions of flake removals. Instead, the apparent standardization of core forms is likely the product of the technological constraints of the centripetal reduction strategies used. Whatever the ultimate explanation, however, it casts strong doubt on the reliability of equating high levels of redundancy of artifact form with the active imposition of design standards to final products.

TECHNOLOGICAL CONSTRAINTS 2: COMPARISON OF BIFACES AND FLAKE TOOLS

As argued above, the range of possible shapes for bifacial handaxes is limited by the technological constraints of bifacial reduction as well as post hoc criteria for the definition of a "handaxe," neither of which is related to prehistoric design standards. The effects of these particular constraints on the shapes of bifaces can be seen in comparisons of handaxes and sidescrapers from beds 72I, 73S, and 74S at Tabun cave. Figures 6.4a–6.4c compare variation in length, length/width ratios, and width/thickness ratios for samples of bifacial handaxes and simple sidescrapers (Bordes's types 9–11) from these three layers.

In all three assemblages, the scrapers and bifaces show similar levels of variation in size (length), in that there is a great deal of overlap in the 95 percent confidence intervals for the respective CV values. However, the bifaces are consistently less variable than scrapers with respect to shape (length/width and width/thickness ratios). All of these artifacts were made by the same hominins, so different capacities or abilities are not implicated in the different degrees of "standardization" apparently exhibited by the two artifact types. On the other hand, the mechanical constraints of bifacial tool production would certainly have had a strong influence on shapes of handaxes, especially the relationships between width and thickness. The shapes of sidescrapers, in contrast, are mechanically free to vary within broader limits. Arbitrary boundaries between typological categories, particularly handaxes, discoids, and disc cores (Dibble 1989), may further narrow the range of shapes exhibited in artifacts classified as handaxes; in this case, the effect would be most strongly expressed in the range of length/width ratios.

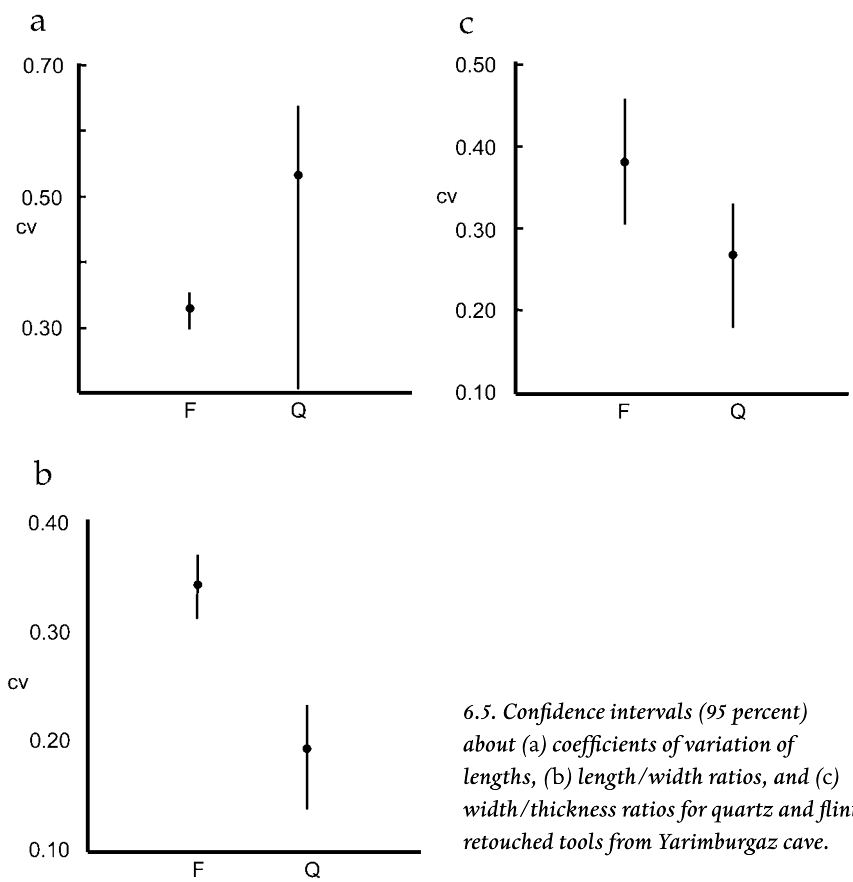




*6.4. Confidence intervals (95 percent) about (*a*) coefficients of variation of lengths, (*b*) length/width ratios, and (*c*) width/thickness ratios for sidescrapers and bifaces from Tabun cave.* S *indicates sidescrapers;* B *indicates bifaces.*

RAW MATERIAL FRACTURE QUALITIES: YARIMBURGAZ QUARTZ AND FLINT

The lithic assemblage from Yarimburgaz cave provides an opportunity to examine the possibility that raw material properties, especially preferential fracture, could lead to unusual degrees of morphological redundancy in Paleolithic artifacts. Most artifacts from Yarimburgaz, flake tools in particular, are manufactured using flint or vein quartz/quartzite, materials with very different fracture properties. Figures 6.5a–6.5c show the coefficients of variation and bootstrapped confidence intervals for one linear measurement (length) and two measures of shape (length/width ratio and width/thickness ratio) for unbroken retouched tools of flint and quartz from Yarimburgaz. The sample coefficient of variation for length is much higher for quartz tools than for flint (Figure 6.5a), although the confidence interval for quartz is so large that it is difficult to say whether the difference is statistically significant. In contrast, coefficients of variation for both measures of shape (Figures 6.5b, 6.5c) are significantly lower for quartz than for flint: in neither case do the confidence intervals contain the actual CV values for



6.5. Confidence intervals (95 percent) about (a) *coefficients of variation of lengths,* (b) *length/width ratios, and* (c) *width/thickness ratios for quartz and flint retouched tools from Yarimburgaz cave.*

the other sample. Contrary to what might be expected based on general perceptions about the qualities of different raw materials, the shapes of quartz artifacts appear to be more highly "standardized" than those of flint artifacts.

Because all of the artifacts involved are part of the same assemblage and were produced by the same hominins, and because the same basic set of tool forms is represented in both raw materials (Kuhn, Arsebük, and Howell 1996), it would be difficult to argue that the differential "standardization" of flint and quartz tools is intentional. Rather, the regularity in the shapes of quartz tools would appear to stem from the unique fracture tendencies of this particular raw material. The flint used at Yarimburgaz is quite homogeneous, with normal conchoidal fracture. In contrast, the milky vein quartz (or quartzite) used at the site tends to fracture preferentially along boundaries between large crystals.

This tendency often results in flakes with rhomboidal or diamond-shaped cross-sections, adding to the redundant shapes of tools and tool blanks.

WHAT CAN WE REALLY SAY ABOUT STANDARDIZATION?

There is little doubt that the Pleistocene hominids sometimes aimed to achieve a particular range of sizes and shapes in their stone tools. However, the ability of archaeologists to identify the metric and morphological targets of ancient tool makers based on levels of formal redundancy is less certain. The analyses above demonstrate that mechanical constraints on technological procedures as well as physical properties of different raw materials can impose limits on the shapes and sizes of artifacts, producing what might be construed as evidence for intentional standardization where there is no reason to expect that any such standards were actually applied.

Two objections to the findings presented above can be anticipated. One is that no competent analyst would ever mistake unusually high levels of similarity among cores or quartz tools as evidence for the imposition of special design criteria to these artifacts. The second is that the measurements employed provide only the crudest estimates of the morphology of Paleolithic tools. As for the first point, the primary aim of this study is to show that the *appearance* of standardization can occur even where there is no reason to believe that special standards were actually imposed. The fact that these are rather extreme examples in no way diminishes the likelihood that the same factors may influence artifact morphology where causality is less obvious. As for the measures used, they were selected specifically because they *are* commonly employed by lithic analysts; moreover, they have in fact been used as arguments for and against the imposition of arbitrary design features on Paleolithic tools (Chazan 1995; Gowlett 1987; Marks, Hietala, and Williams 2001; Monnier 2005). Certainly, these simple measurements do not adequately describe artifacts, and other features might better reflect the application of arbitrary rules of design. On the other hand, if raw material, reduction, or the mechanics of stone fracture can act to inhibit or promote variability in simple metric attributes, they can certainly influence other measurements as well.

The results presented here have a number of implications for approaches to the issue of standardization in Paleolithic technologies. Most obviously, assertions about imposed standardization of artifact forms require comprehensive attempts to eliminate effects of variables other than the applications of design standards. When possible, comparative studies must control as much as is practical for the potential effects of raw material fracture characteristics, technologies of blank production or shaping, and differential reduction. It is also crucial to have some comparative standard against which relative degrees of within-group uniformity can be assessed. It is not very meaningful to refer to a statistical measure of variation as evidence for standardization unless there is some evidence that it documents an unusual degree of uniformity. Unretouched artifacts, cores, or presumably unstandardized "expedient" tools would make good controls.

Even with these caveats, studies of standardization based on the sizes and shapes of retouched stone tools will always be problematic simply because the morphologies of artifacts are subject to such a wide range of influences. Any study based exclusively on the shapes of retouched tools must conflate the results of a number of more or less independent influences and a whole series of actions (blank production, blank selection, retouch, resharpening) into a single set of observations about what "finished tools" look like. It is seldom possible to gain analytical control over all of these factors simultaneously. In searching for regularities and rules of Paleolithic technological behavior, it may be better to look elsewhere, to focus on technological phenomena from which it is more practical to isolate arbitrary choices and specific nodes of decision making.

The procedures entailed in the production of artifacts (*chaînes opératoires*) and patterns of raw material selection and exploitation are two areas of lithic studies that possess considerable potential to yield information on the nature of design standards in Paleolithic technologies. Indeed, many researchers have already focused their efforts in these directions (e.g., Boëda 1990, 1991; Gowlett 1996; Martínez 1998; Roche et al. 1999). Both the procedures of artifact production and the selection and exploitation of raw materials involve distinct sequences of actions that can be reconstructed from studies of archaeological artifacts informed by experimental research. These sequences can in turn be modeled as a set of problem-solving strategies. One the main attractions of the *chaîne opératoire* approach is that "it fosters an explicit concern over the processes, and not just the states of material culture" (Schlanger 1994:143). More to the point, it takes those processes as the object of study.

Although studies of technological procedures are highly promising sources of information about arbitrary design choices and standardization in the ancient past, current analytical strategies are not well-suited to this particular task. Investigations of *chaînes opératoires* tend to be highly normative, focusing mainly on idealized, "modal" tendencies (Bar-Yosef and Van Peer 2009). Such an analytical perspective may be appropriate for researchers trying to understand technical lineages and learning frameworks or attempting to establish levels of competence or "technicity." However, normative approaches concentrating on ideal technical outcomes are inherently unsuited to examining levels of standardization and redundancy.

Studying *chaînes opératoires* as standardized *designs* would entail a refocus of research efforts. First, it is crucial to assess the basic mechanical problems faced by tool makers. In fact, most analysts have a good intuitive understanding of mechanical limitations in stone flaking, but this knowledge could itself be more standardized. The optimal outcome would be to establish the range of *possible* variation in technological behavior by calibrating constraints imposed by the mechanics of stone fracture and the working properties of particular raw materials. With respect to "operational chains" of manufacture, it is particularly important to know whether associated attributes and sets of procedures are linked mechanically or whether they represent more or less arbitrary decisions; for example, how much of a particular pattern of core reduction follows from the early shaping of the core and how much from the shapes and sizes of nodules used (e.g., Isaac 1986; Kuhn 1995b; Kuhn, Arsebük 1996; Schick and Toth 1993:130)?

Examining how tactics of manufacture or raw material use varied as the problems faced by stoneworkers changed, particularly over the short term, may be one of the best ways of identifying decision nodes in extinct technological systems. As reduction proceeds and the shape of the core changes, the options available to the knapper change as well, forcing the worker to modify his or her tactics in order to achieve the original end (Pelegrin 1990). Stereotypical sequences of actions, executed regardless of the previous shape of the workpiece, would represent a very different kind of learned behavior or "design" than, for example, application of different procedures to achieve a particular shape or geometry from a variety of different starting points (Belfer-Cohen and Goren-Inbar 1994; Karlin and Julien 1994:156). In the long run, it may also be more profitable to look to errors rather than to successful execution of particular procedures. A single mis-strike or a hidden flaw in a piece of stone can make even the most proficient knapper scramble just to salvage some utility from the workpiece. A tool maker's response to unanticipated errors or defects in raw materials is perhaps the single best indicator of the goals of a particular knapping episode. Such an approach has been applied successfully to late Upper Paleolithic blade technology (e.g., Karlin et al. 1992; Ploux 1991).

The other element missing from current approaches to studying *chaînes opératoires* is a means of assessing and comparing variability within and among assemblages. Concentrating on the best examples of handaxes or a few completely refitted Levallois cores is akin to a behavioral psychologist counting only the rats that succeed in navigating a maze. Once hypothetical goals of a technological system have been nominated, the important question with respect to standardization is how well and how often artisans actually realized those goals. This may be the most difficult nut to crack. Approaches to isolating, characterizing, and describing *chaînes opératoires* in the production of lithic artifacts are highly diverse and often incommensurate; a comparison of contributions to recent volumes on Levallois (Dibble and Bar-Yosef 1995) and discoid core technology (Peresani 2003) illustrates this phenomenon very well. Most certainly it will require introducing a level of quantification into what is currently a fundamentally non-quantitative enterprise. Methods developed by Van Peer (1992) provide one model for comparability in describing lithic *chaînes opératoires*.

Archaeologists working in early time ranges have only recently begun to pay close attention to selectivity and choice in raw material exploitation (Belfer-Cohen and Goren-Inbar 1994; Braun et al. 2009; Martínez 1998; Roche et al. 1999; Stout et al. 2005). All tool makers must cope with the inherent physical properties of different sorts of stone. The texture, ease of fracture, and homogeneity of different types of stone have marked effects on the feasibility of alternative approaches of core reduction. The effective exploitation of a novel raw material often requires adjustments in basic techniques and procedures, and it may be necessary to use very different procedures in order to make the same kinds of end products from different types of stone. Similarly, the shapes and sizes of packages in which stone occurs can have a strong influence on how knappers achieve their goals. Moreover, specific raw material qualities can be measured and linked experimentally to specific dynamics of stone fracture and tool use (Braun et al. 2009; Plummer 2004:131). How Pleistocene hominids dealt with these constraints, the technical flexibility they exhibited in making use of raw materials with diverse properties, should be particularly useful in identifying redundancies in strategies in artifact production and, in some cases, may serve as a means of differentiating closely related operational sequences.

NOTES

1. The constraints of artifact function are not considered separately from artifact design. It is usually difficult to separate the purely stylistic aspects of artifact morphology from the functional ones. More importantly, whether a tool is shaped to fit stylistic convention or perceived function is irrelevant to the argument at hand—it is still a matter of producing a standard morphology.

2. There are a few exceptions that involve either particular raw materials such as limestone (Sahnouni, Schick and Toth 1997) or hammer-and-anvil percussion.

3. Gowlett (1987:253) provides a list of five "concepts" demonstrated by the common properties of a group of Acheulian bifaces. At least three of the concepts are simple

consequences of confining the discussion to bifacially worked artifacts. The remaining two elements (a well-developed long axis with a tendency toward bilateral symmetry around this axis) would seem to stem from the criteria used to distinguish handaxes and cleavers from other items worked on both faces.

4. This point is also noted by Gowlett (1996:209).

5. The procedures were carried out using the software Resampling Stats, version 3.14 (for MS-DOS) (Bruce 1993).

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SEVEN

Middle Stone Age Stone Tools from Klasies River Main Site and Symbolic Cognition

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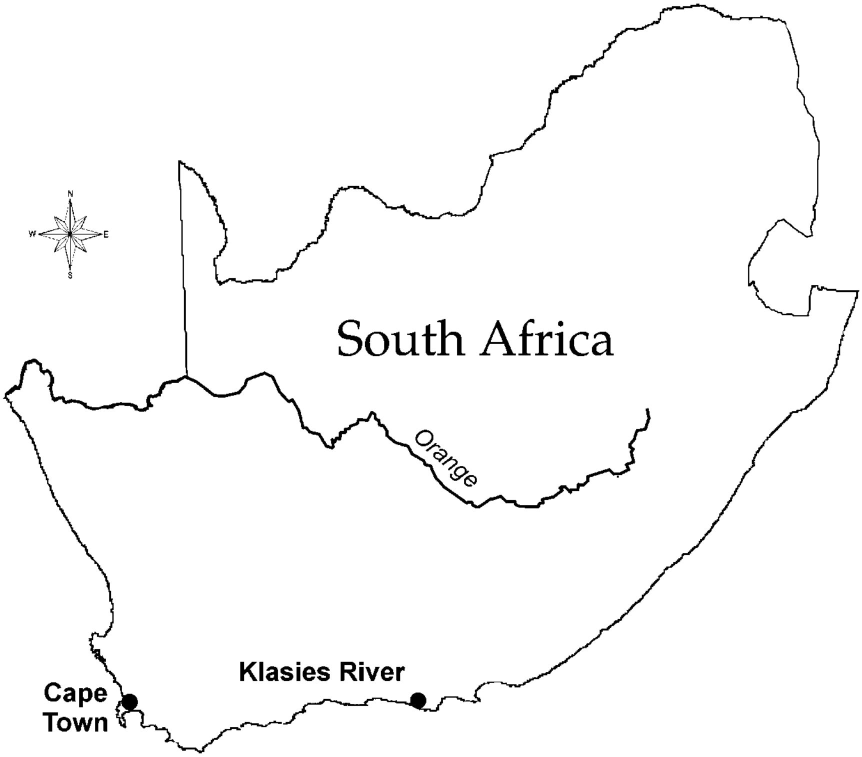
ABSTRACT

Klasies River, a well-known South African occurrence, preserves Middle Stone Age archaeological material dating to between 60,000 and 120,000 years ago. This site produced a large sample of stone artifacts that, in a well-stratified and meticulously excavated context, provides a window into the technological behavior of early anatomically modern humans of the southern Cape. Four technocomplexes, the MSA 1, MSA 11, Howiesons Poort, and MSA 111 occur at Klasies River. This chapter discusses the first three of these complexes and describes and interprets their clearly differentiated technological characteristics. For example, the use of a soft hammer can be detected only in the MSA 1 and Howiesons Poort; the MSA 1 and Howiesons Poort are blade strategies in which similar elements of platform preparation can be discerned; the MSA 11 is characterized by removal of products in a Levallois unipolar strategy using hard-hammer percussion exclusively. It is only in the Howiesons Poort that a clearly recognizable typological component, backed artifacts, can be observed. Whether the technocomplexes at Klasies River are relevant to the evolution of symbolic capabilities is considered. This is discussed within the context of the biological correlates

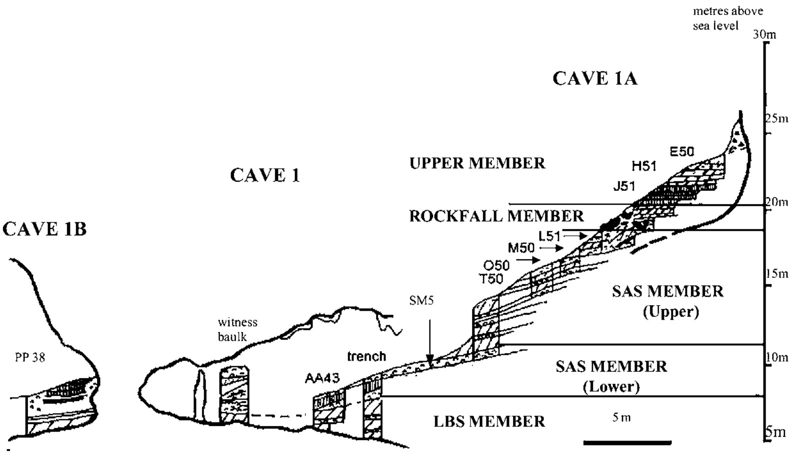


7.1. Map of Klasies River, South Africa.

of symbolic representation, stylistic and typological variability, innovation, and technological sophistication

INTRODUCTION

The Klasies River main site, situated on the southern Cape Coast of South Africa (Figure 7.1) (Deacon 1995; Singer and Wymer 1982) consists of a complex of caves (Caves 1, 1A, 1B, 2) that collectively contain the evidence of the lifeways of humans that lived between 120,000 and 60,000 years ago. The original deposit of twenty-one meters was much eroded by a rise in sea level around 6,000 years ago, but the remnant still produced a very large archaeological sample. J. Wymer carried out extensive excavations in 1967/68 and published the results in the 1982 monograph *The Middle Stone Age at Klasies River Mouth in South Africa* (Singer and Wymer 1982). In 1984, H. J. Deacon commenced with a new generation of excavations. He sampled a column through the sequence exposed by the Singer and



7.2. Stratigraphy of the Klasies River sequence (after Deacon and Geleijnse 1988).

Wymer 1967/68 excavation using microstratigraphic units, resulting in artifact samples that are relatively smaller than those of the 1967/68 excavations.

Singer and Wymer (1982) recognized five culture stratigraphic divisions: the basal unit, the MSA 1, followed in stratigraphic order by the MSA 11, Howiesons Poort, MSA 111, and MSA 1V. Deacon (Deacon and Geleijnse 1988) further grouped the MSA 111 and Howiesons Poort in the Upper member, the MSA 11 in the SAS member, and the MSA 1 in the RBS and LBS members (Figure 7.2). This chapter discusses the lithic patterning at Klasies River; Wymer's excavation produced 255,244 lithic artifacts (Singer and Wymer 1982) and that of H. J. Deacon 80,000 (Deacon 1995; Deacon and Geleijnse 1988; Wurz 2000). Primarily the lithics from the Deacon excavation (the Deacon sample) will be discussed, but where sample sizes were small, it was amplified by the Singer and Wymer collection. There have been different interpretations of the stone tool patterning in the Klasies River sequence. Some interpretations of the lithics at Klasies River emphasize continuity and stability over millennia. Singer and Wymer (1982:64), for example, concluded that the changes in the sequence are "not very marked," and Thackeray (Thackeray and Kelly 1988) remarked that the Klasies River assemblages are typified by typological and technological continuity throughout. This perceived lack of variability in the Middle Stone Age has been one of the reasons for excluding early modern humans from the grade of "modern" human behavior (e.g., Klein 2000, 2008; Mithen 1996; Noble and Davidson 1996; Thackeray 1992; Wadley 2001). A subsequent study that explored variability in the sequence by using technological variables and multivariate discriminate analyses (Wurz 2002, 2005; Wurz et al. 2003) noted a more marked degree of variability and concluded that the substages at Klasies River represent clearly recognizable techno-complexes. The issue addressed in this chapter is whether this technological behavior can be equated with the technological behavior of extant human populations whose actions are guided by symbolism. The MSA 1, MSA 11, and Howiesons Poort from Klasies River are discussed in the context of symbolic behavior and its palaeonthropological and archaeological indicators.

SEMIOTICS AND SYMBOLIC REPRESENTATION

The modern mind and behavior is typified by symbolic behavior (Deacon 1997a, 1997b, 2003; Gould 1980; Mithen 1996; Noble and Davidson 1996; Wynn 1991). The nature of symbols and symbolism has been the subject of extensive literature in the fields of linguistics, psychology, and philosophy, but the semiotic theories developed by De Saussure and Peirce (Sinha 1996) have been particularly influential in discussions on archaeology and symbolism. Three categories of signs occur: icons, which realistically resemble what they represent; indexes, which are correlated with something else in time and space; and symbols, in which the only link between a signifier and signified is a social convention or an arbitrary code understood by a group of people. According to Deacon (1997a), these levels of sign can be related to different kinds of representation. Representation is achieved by neuronal actions that allow a sign and its referent to be associated and interpreted (Deacon 1988, 1997a, 1997b). A fairly simple mnemonic strategy is involved in the representation of icons and indexes (Deacon 1997a). The basic level of representation is recognition, which allows iconic reference, whereas indexes are recognized through the interpretive process of association. These responses are produced as if the signified was present.

Symbolic representation that typifies human language is radically different from iconic and indexical representation because it marks a shift from associative to symbolic predictions. The signs need to be re-represented and this involves discovering a system, or higher-order regularities. "Unlearning" of associations has to take place to make the construction of rules about classes of combinations possible. Things become represented within a distributed web of reference. In the web, the relationship that a referent has to an object is also a function of the relationship it has to other symbols (Deacon 1997a; Edelman 1987). For example, the word "cat" is simultaneously associated with dog, animal, meow, and words that rhyme with cat. It is via unlearning that the common chimpanzees, Austin and Sherman, were taught to communicate with symbols. It took thousands of trials to teach them to shift attention from token-object relations (indexical) to token-token (symbolic) relations by unlearning the concrete association in favor of a more abstract one (Lloyd 2004; Savage-Rumbaugh 1986; Savage-Rumbaugh and Lewin 1994). Humans have little difficulty with these kinds of tasks because they evolved the potential for specialized neural architecture for symbolic representation.

Comparisons with primate brains suggest that the out-of-proportion evolution of certain parts of the brain—for example, the prefrontal cortex (Deacon 1997a, 1997b; Rilling 2006; Schoenemann 2006) and the cerebellum (Rilling 2006; Weaver 2005)—or specializations in the areas connected by the arcuate fasciculus (Rilling et al. 2008) are important in this regard. The increase in brain size in *Homo* could be regarded as proxy evidence for the evolution of specialized neural architecture and brain reorganization (Deacon 1997a). In the process of brain enlargement different organization is necessary because it becomes impossible to connect all brain areas to maintain brain function (Deacon 1988, 1997a, 1997b; Kien 1991). Although a bigger brain is often assumed to be related to more computing power, it has no relationship to greater intelligence or symbolic abilities (Deacon 1997a; Holloway 2008; Roth and Dicke 2005).

To know whether the increase in brain size was punctuated or gradual provides an important perspective on the evolution of symbolic capabilities. The increase in cranial capacity has been described as gradual (Deacon 1997a; Lee and Wolpoff 2003; Schoenemann 2006) but also as punctuated (Aiello 1996; Groves 1989). When brain size relative to body mass is considered, it is apparent that there was a rapid increase in encephalization only among Middle Pleistocene *Homo* (Rosenberg, Zune, and Ruff 2006; Ruff, Trinkaus, and Holliday 1997). This means that stasis in brain size occurred between 1.8 million and 600,000 years ago (Conroy et al. 2000; Ruff, Trinkaus, and Holliday 1997) with significant brain enlargement only taking place after 600,000 years ago. It is only Middle Pleistocene fossils that date to between 600,000 and 300,000 years ago, such as Bodo, Kabwe, Petralona, Arago, and Dali, that have absolute and relative brain sizes larger than those of *H. erectus* (Rightmire 1998, 2004, 2008). Around 200,000 years ago the smaller end of the range of variation in brain size disappeared (Davidson 1999; Groves 1989:302). It is unlikely that the relatively rapid increase in encephalization in the Middle Pleistocene can be related to mechanisms such as "magic mutations" and "hopeful monsters" (Deacon 1997a; Greenberg et al. 1999; Szathmáry 1999:745) or that the increase in brain size as such played a causal role in the development of new symbolic and technological behaviors. It is more likely that symbolic (Deacon 2003) and technological (Stout and Chaminade 2009; Stout et al. 2008) behavior drove the direction of genetic changes toward the modern condition in a coevolutionary process (Deacon 2003). The Middle Pleistocene thus appears to be an interesting period in terms of brain evolution in which some symbolic capabilities must have existed already. A number of theoretical perspectives have been developed to identify symbolic aspects in Paleolithic stone artifacts.

SYMBOLIC COGNITION AND STONE TOOLS

The markers used to recognize "symbolism" in stone tools have hardly changed since the inception of archaeology—concepts such as creativity and innovation have been used since 1924 (Landau 1991). Indicators such as typological standardization and typological variety in time and space (Byers 1994, 2001; McBrearty and Brooks 2000; Noble and Davidson 1996; Wadley 2001) have also been linked to symbolic behavior. Recently McBrearty and Brooks (2000:492) listed lithic attributes—for example, "new" technologies like blades, microblades, and backing; standardization within formal tool categories; hafting and composite tools; special-purpose tools; increased numbers of tool categories; and geographic and temporal variation in formal categories and regional artifact styles—as indications of human inventiveness and capacity for logical thinking. However, concepts like inventiveness, capacity for logical thinking, creativity, and innovation have little operational value if the relationship between them and symbolic communication, or language, is not developed theoretically.

One of the more detailed discussions on stone tool variability and symbolic behavior can be found in the debate on style. In its earlier manifestation, the relationship between style and symbolism was sought in the identification of active intentional style, but the distinction between active intentional style and unintended passive or isochrestic style is now considered redundant (Byers 2001; Chase 2003). Chase recently defined style as "a given pattern or a set of patterns consisting of overdetermination of form that are, in one way or another, associated with a given group of people bounded both ethnically and temporally" (Chase 2003:26). Style thus may be imposed on material culture because of adherence to group standards and norms concerning the manufacture of stone tools (Chase 2003) and this can also be described as a convention (Davidson 2003). The symbolic aspect of style lies in the tradition, or rules that govern form, consciously or unconsciously. Repeated incidences of overdetermination of form or imposed form demonstrate conscious planning and forethought (Noble and Davidson 1996). It involves arbitrary conventionality that is not possible without using symbolic language. Byers (1994, 2001) also explicitly relates the norms and standards by which artifacts are made to referential symbolism, and he points out that even though such norms and conventions may rely on referential symbolic capabilities, the artifacts themselves may not have referential meaning.

Lycett and Gowlett (2008), in their discussion on whether the Acheulian represents a "tradition," point out that the skills involved in making handaxes may have been transmitted via social rather than cultural processes. Socially acquired regional patterns of behavior that are similar to the cultural "traditions" of humans can be recognized in nonhuman primates (Lycett, Collard, and McGrew 2007; van Schaik et al. 2003; Whiten et al. 1999). Furthermore, it may not be possible to conclusively show that stylistic variability is the result of communication over time and space by means of symbolic reference. The spread or persistence of stone tool traditions on a geological time scale (Chase 2003) cannot be observed and it is not possible to predict how a group of technologically sophisticated individuals would act outside a symbolic referential framework. Therefore, stylistic conventions or "traditions" in stone tools are not necessarily the result of symbolic cognitive capabilities. However, stone tool production is a highly skilled behavior (Bamforth and Finlay 2008; Bleed 2008)—handaxe production from around 500,000 years ago is, for example, evidenced by multi-step actions that were guided by higher-level intentional organization (Stout and Chaminade 2009; Stout et al. 2008). Whether the regional patterns of behavior observed in nonhuman primates represent such levels of skill and whether these can be transmitted via social processes is a noteworthy question.

A number of approaches have been developed that integrate archaeological and biological evidence to interpret stone tool variability through time in terms of symbolism. The integration of archaeological and biological evidence is essential in theories on the evolution of symbolic capabilities (Mellars 2005). Stout and colleagues (2008) investigated functional brain activation during expert experimental production of Oldowan and Acheulian artifacts and found that handaxe, but not Oldowan tool, production involves neural circuits that partially overlap with language circuits. They concluded that although handaxe production does not provide direct evidence for language capacities, it reflects similar hierarchical processing capabilities. Holloway's (1969) hypothesis, that stone tools indicate capacities analogous to linguistic abilities in the realm of manual action organization, and that of Greenfield (1991), that selection acting on tool making could have contributed to the evolution of language-relevant circuits through developmental displacement, are seen as relevant in developing insight into the relationship between the evolution of language and stone tool technology (Stout and Chaminade 2009).

Levallois and blade technology associated with the Neandertals and African Middle Stone Age *Homo sapiens* have been interpreted as a reflection of expert performance or cognition but not modern linguistic thinking (Coolidge and Wynn 2004; Wynn and Coolidge 2004). Wynn and Coolidge suggest that these technologies rely on long-term working-memory capabilities that have been in place before the evolution of symbolic capabilities (see also Wynn and Coolidge, Chapter 5). It is only with the evolution of enhanced working memory that modern levels of innovation and creativity in stone tools were possible. Upper Paleolithic variability that reflects enhanced working memory is evident in "comparatively rapid changes in technology and artifact style" (Coolidge and Wynn 2004:62). Enhanced working memory would have made the mental rehearsal and "thought experimentation necessary for effective innovation" (Coolidge and Wynn 2004:65) in stone tools possible. It might have been a mutation in the brain around 50,000 years ago that through rewiring of neural pathways allowed enhanced working memory (Coolidge and Wynn 2001).

Klein (2008; Klein and Edgar 2002) also proposes that a mutation might have enabled fully modern cognition around 50,000 years ago. The diversity and standardization of artifact types, the rapid increase in the rate of artifactual change through time, and the degree of artifact diversity through space are listed as the stone tool features that reflect an "innovate burst." He (Klein 2008:270) emphasizes that these traits should not be considered as evidence of "modern" behavior in isolation but that their appearance as part of a "package" is meaningful. In the discussion in this section much turns on the specific interpretation of concepts such as stylistic and typological variability, technological sophistication, rapid, and innovation. A lithic analyst may define these qualities differently than a cognitive scientist. Despite this ambiguity, these theories provide a constructive context for interpreting technological variability in stone tools.

THE MSA SEQUENCE AT KLASIES RIVER

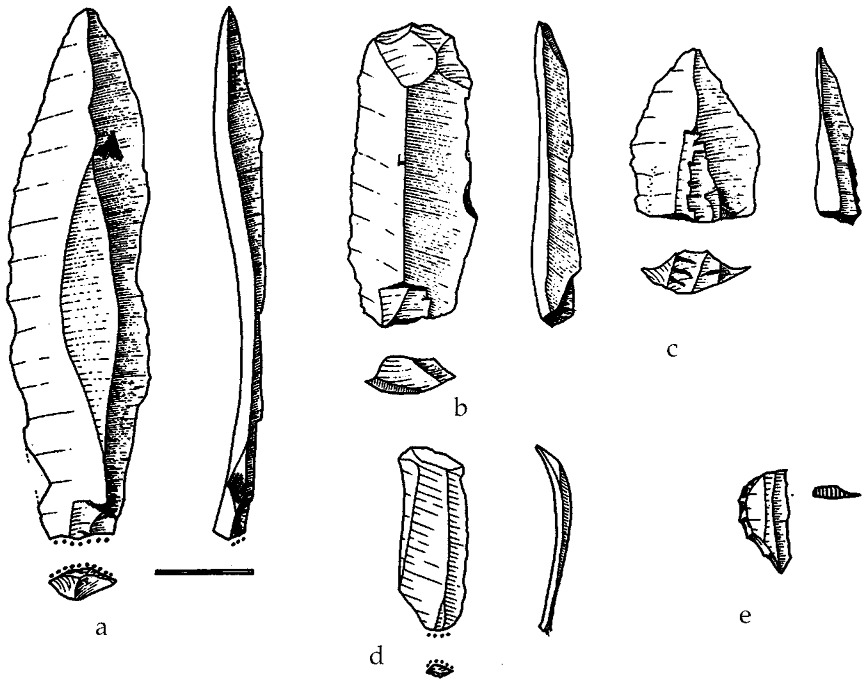
The methodology used to analyze stone artifacts strongly influences the patterning that can be perceived. Assessment of stylistic variability in Middle Stone Age assemblages in South Africa has conventionally been based on the typological study of retouched types and metrical attributes of flaked products. This methodology is capable of capturing only a limited degree of variability in the Middle Stone Age with its low frequencies of unstandardized retouch. Types do occur in the Middle Stone Age—for example, the backed artifacts in the Howiesons Poort (Deacon 1989; Soriano, Villa, and Wadley 2007; Wurz 1999), hollow-based points (Kaplan 1990), and unifacial and bifacial points (Villa et al. 2009a; Wadley 2005)—but generally it is characterized by low frequencies of retouch. The French *chaîne opératoire* approach (Sellet 1993; Shott 2003; Soressi and Geneste 2006) provides an extended framework for the study of Middle Stone Age artifacts, despite the fact that the principles of the *chaîne opératoire* approach are sometimes obscure to those not intimately familiar with subject assemblages (Hovers 2007:54). The Klasies River lithic assemblages were analyzed using conventional typological and metrical analysis in conjunction with concepts of the *chaîne opératoire* approach. Variables such as core geometry, the notion of "end products," and technological features were used to infer technological preferences (Wurz 2002, 2008; Wurz et al. 2003). The MSA 1, MSA 11, and Howiesons Poort artifact assemblages from Klasies River are discussed below.

MSA 1

The MSA 1 or Klasies River industry (Wurz 2002) from the LBS member, the lowest stratigraphic division in Cave 1 and Cave 1A, accumulated in Marine Isotope Stage (MIS) 5d at 110,000 years ago (Deacon, Talma, and Vogel 1988; Feathers 2002; Vogel 2001). During this period the faunal composition indicates a comparatively open habitat—grazers such as equids and alcelaphines were relatively more prominent during this period than the subsequent MSA 11 phase (Klein 1976; Van Pletzen 2000). Pelagic fishes, such as maasbanker and the Indian scad, make up 20.6 percent of the fish remains in the LBS member in contrast to the low representation of these species in the Upper and SAS members. It is likely that humans were agents of collection of the fish in the MSA 1 and other substages (Van den Driesch 2004).

Almost all of the MSA 1 artifacts (98 percent) are in quartzite from the beach cobbles that occur adjacent to the site. A recurrent blade strategy, guided by a Levallois-type conception (Wurz et al. 2005), was used. In general, the MSA 1 blades (Figure 7.3a) and points are longer and thinner than those of the MSA 11 and they often have curved profiles. Some of the platforms have diagnostic criteria that indicate the use of a soft hammer. On a third of blades and points a small platform size, the presence of a lip, a platform angle of less than 80 degrees, abrasion or thinning to remove the overhangs of the previous removals, a diffuse platform, and the absence of marks that indicate the impact of percussion (Inizan et al. 1999; Pelegrin 2000) occur. The retouched component in the MSA 1 in the Deacon sample is very low with only 5 of 543 elongated products being denticulated and none retouched.

No other contemporary assemblages with these characteristics have been described from the southern Cape or from the rest of South Africa. The MSA 1 cannot be regarded as a convention or a durable tradition of flaking in space and time, but it is innovative in the sense that it is a blade technology in which the soft-hammer technique was used. It is interesting that the Howiesons Poort substage, 65,000 years ago, shows many of the same technological features as



*7.3. (*a*) MSA 1 blade, cave 1; (*b*) MSA 11 blade, cave 1; (*c*) MSA 11 point, cave 1; (*d*) Howiesons Poort blade, cave 1A; (*e*) Howiesons Poort backed artifact, cave 1A.*

the MSA 1 (Wurz 2002). The MSA 1 at Klasies River represents a well-established techno-complex, and the absence of similar assemblages may simply reflect the understudied nature of the South African Middle Stone Age.

THE MSA 11

The MSA 11 or Mossel Bay industry (Wurz 2002) occurs in the ten-meter-thick SAS member (Deacon and Geleijnse 1988) that spans a time range of some 25,000 years, between 100,000 and 78,000 years ago (Vogel 2001). According to Deacon and colleagues (1988), the SAS member correlates with MIS 5c and also with MIS 5b. An ecological shift from the LBS member is indicated by the relative frequencies of browsers and mixed feeders like *Raphicerus* species (grysbok) and tragelaphines like kudu and bushbuck, which prefer a more closed environment. Fish remains are mostly of intertidal and estuarine species (Van den Driesch 2004). The environment in MSA 11 times at Klasies River was particularly productive. Van Dijk (2006) remarks that few Quaternary sites have as many frog families, genera, and species as this occurrence.

As in the MSA 1, quartzite cobbles were used as blanks for cores to produce MSA 11 tools. Almost all of the cores studied are exhausted and have a point scar as last removal. The mean length of the points is similar to the mean length of the cores, suggesting that the cores were so reduced in volume that it was no longer possible to reprepare them. A unipolar Levallois point production strategy (Wurz 2002) can be inferred, but other reduction strategies not readily comprehensible with the available data must have been used. Neither the cores nor the end products evidence the rubbing or the intensive platform preparation of the MSA 1 or the Howiesons Poort. In the MSA 11, percussion blows were aimed well back from the dorsal edge of the platform, and only a hard hammer was used to remove products, resulting in products with straight profiles (Figure 7.3a–b). Many of the products have a splintered bulb of percussion and a "ring-crack" at the point of impact, typical of hard-hammer percussion (Inizan et al. 1999; Pelegrin 2000), as well as a prominent bulb of percussion. Formal retouch is infrequent and restricted to sharpening the tip or shaping the butt. However, some type of "informal retouch" (Wurz 2000) in the form of edge modification is relatively common and found on about half of the points.

The points and blades of the MSA 11 are different from those in the MSA 1 in a technological sense, as is readily apparent in terms of piece and platform size and profile. Others have interpreted the MSA 1 and 11 as not significantly different from each other (Singer and Wymer 1982; Thackeray 1989; Thackeray and Kelly 1988), and therefore, some level of verification through statistical analysis was sought. Extensive univariate and multivariate statistical analysis of continuous variables of the blades and points from the MSA 1 and 11 have been undertaken (Wurz 2005; Wurz et al. 2003). The variables of platform thickness and piece length significantly discriminated between the MSA 1 and MSA 11. To evaluate the success of the discriminating procedures, a CVA biplot resubstitution classification procedure was done and this has shown that unprovenanced blades and points could be identified as MSA 1 or MSA 11 with a success rate of 80 percent. These results increase confidence that the MSA 1 and MSA 11 are two technologically distinct substages.

The MSA 11 is the most substantial substage at Klasies, but as of yet, it is not possible to correlate this substage with other assemblages in South Africa. Goodwin and Van Riet Lowe's (1929) Pietersburg may be similar, but because few South African assemblages have been described in terms of technology, intersite correlations are problematic. The use of the Levallois or prepared core reduction strategies in the MSA 1 and MSA 11 imply knowledge of hierarchical relationships of the volume of the core. In prepared core technology the cores are prepared or "set up" according to specific geometric principles to achieve products of particular dimensions. This may reflect hierarchical language-like processing capabilities, a hypothesis that may receive support in future investigation on the evolution of symbolic capabilities.

HOWIESONS POORT

The Howiesons Poort at Klasies River is from the Upper member, and dates of 65,000 years ago (Vogel 2001) and between 64,100 and 65,500 years ago (Jacobs et al. 2008) have been published for this assemblage. Deacon and colleagues (1988) suggested that it is associated with MIS 4, a three-quarter glaciation related to a period of sea regression when the coast would have been within ten kilometers of its present position (Deacon, Talma and Vogel 1988). This techno-complex at Klasies River has been associated with a less productive environment (Ambrose 2006; Deacon, Talma and Vogel 1988; Minichillo 2006), whereas Jacobs and colleagues (2008) relate it to a period of climatic warming. The faunal record shows that, as in MSA 1 times, there is a relative increase of obligate grazers like springbok (*Antidorcas* sp.) and *Pelorovis antiquus*, indicating a more open habitat (Klein 1976; Van Pletzen 2000). More or less the same types of fish species occur in the Howiesons Poort and the MSA 11 (Van den Driesch 2004).

In the Howiesons Poort (Deacon sample) there is a fivefold increase, relative to the MSA 11, in the use of non-quartzite raw material. The non-quartzite component consists of silcrete, quartz, chalcedony, and hornfels, but quartzite (67 percent) is still the dominant raw material used. The source of the nonlocal material is not known, but it is possible that it occurred locally as pebbles in riverbeds (Minichillo 2006). In the Howiesons Poort of Klasies River a blade core reduction system was aimed at obtaining blade blanks. The cores in quartzite and non-quartzite at Klasies River were worked in the same way, even though the non-quartzite cores are smaller—there is no evidence that the non-quartzite cores were worked "more methodically" (*contra* Singer and Wymer 1982:91).

The Howiesons Poort blades are small-scale versions of those found in the MSA 1, with exactly the same platform thickness to length ratio (Wurz 2002). The same technological features described for the MSA 1 occur on the majority of the Howiesons Poort blades (Figure 7.3d). The rubbing, platform isolation, small platform size, diffused bulbs of percussion, and lipping again probably indicate the use of a soft hammer. The Howiesons Poort became a well-known phenomenon because of the presence of Upper Paleolithic–like backed artifacts (Figure 7.3e) in this early time range. However, backed artifacts are part of the established technological repertoire of the African Middle Stone Age. For example, the Lupemban industry dated to between 300,000 and 200,000 years ago (Barham 2002) have backed artifacts.

The degree of imposed form and standardization of the backed artifacts have been interpreted as evidence for symbolic behavior in the Middle Stone Age of South Africa (Davidson 2003; Deacon 1989; Mellars 2005; Noble and Davidson 1996; Wurz 1999) but not as the origins or onset of modern behavior as sometimes inferred (e.g., Hiscock and O'Connor 2005:63). Thackeray (1992) suggested that the Howiesons Poort backed artifacts do not constitute evidence of modern behavior because they are not as standardized as the Later Stone Age examples. However, a comparison of the coefficients of variation of the Howiesons Poort and Wilton Later Stone Age backed artifacts show similar values (Wurz 1999, 2000, 2002). If the degree of standardization for the Wilton LSA backed artifacts (Deacon 1976) is interpreted as evidence of imposed form or a mental template (Mellars 1991), it implies by extension that the Howiesons Poort backed artifacts have also been produced according to a mental template (Wurz 1999). However, "standardization" is an overused and underdefined concept in lithic studies (e.g., Marks, Hietala, and Williams 2001) and needs to be evaluated against a "baseline" of variation within assemblages (Bamforth and Finlay 2008; Eerkens and Bettinger 2001).

When the coefficients of variation of the blades and points from the other substages at Klasies River are compared to the Wilton and Howiesons Poort backed artifacts (Table 7.1), values that are in the same range occur. Should the inference be made that the MSA 1 and MSA 11 points and backed artifacts with the smaller CVs are more standardized than the other flaked products? Another explanation could be that because both points and backed artifacts are further progressed in the reduction sequence, less scope for size variability existed, and therefore the CVs are smaller.

The Howiesons Poort is the most intensively studied Middle Stone Age occurrence in South Africa. The presence of backed artifacts made intersite comparisons straightforward, and it is known that that the Howiesons Poort has a subcontinent-wide distribution (Deacon 1992). Because different researchers use different research paradigms to study the assemblages, there is limited opportunity to draw more meaningful inter-site comparisons, but there are indications that there are technological similarities between the Klasies River Howiesons Poort and that of Rose Cottage Cave (Soriano, Villa, and Wadley 2007). The Howiesons Poort can be regarded as a convention or durable tradition because the same conventions in terms of retouched types and, most probably, technological standards guided stone tool production in a restricted (Jacobs et al. 2008) time range.

Table 7.1. Average dimensions and coefficients of variation of backed artifacts, blades, and points and Klasies River and Melkhoutboom Wilton.

	Average length (mm)	*Length CV*	*Average width (mm)*	*Width CV*	*Average thickness (mm)*	*Thickness CV*
Wilton backed artifacts Melkhoutboom	11.9 (101)	24				
Howiesons Poort blades	43.9 (45)	29	18.8 (714)	30	4.9 (714)	40
Howiesons Poort backed artifact	36.6 (630)	25.8	15.9 (828)	21.7	4.6 (828)	26.4
MSA 1 blades	81.0 (84)	29	28.3 (472)	29	8.2 (472)	42
MSA 1 points	70.6 (60)	23	33.5 (71)	18	9.3 (71)	24
MSA 11 (lower) blades	75.9 (454)	31	30.2 (1,792)	29	9.6 (1,792)	38
MSA 11 (lower) points	65.3 (414)	25	34.6 (545)	22	11.0 (545)	36

DISCUSSION

The MSA 1, MSA 11, and Howiesons Poort techno-complexes at Klasies River reflect stylistic changes in ways of making artifacts in which specific technological configurations were preferred (Wurz 2002, 2008). The MSA 1, a blade industry, is characterized by long, thin blades and points in quartzite. The platforms are thin relative to piece length and show intensive preparation. In the overlying MSA 11, the typical artifacts are thick, wide-platformed points and blades produced, in part, by a unipolar Levallois technology. The Howiesons Poort, in which a core reduction strategy similar to that of the MSA 1 techno-complex was used, succeeds the MSA 11. The object of core reduction in the Howiesons Poort was to produce short, thin blade blanks that were occasionally retouched into backed artifacts. This techno-complex is further characterized by an increase in the use of nonlocal raw material. The differences among the Klasies River techno-complexes are not the result of the mechanical constraints imposed by the raw material form. Exactly the same size, type, and form of raw material, quartzite cobbles, have been used in the MSA 1 and MSA 11 and for the majority of the Howiesons Poort artifacts, but products of significantly different dimensions and with different technological characteristics were produced. The "dramatic technological reorganization" (McCall 2006; Singer and Wymer 1982) of the Howiesons Poort becomes dramatically less remarkable when seen in the context of the technological principles used throughout the Klasies River sequence. In the Howiesons Poort, techniques that already formed part of the technological repertoire of these highly adaptable humans 110,000 years ago were used.

The succession of techno-complexes at Klasies River is typical of the regional patterning that characterize the Middle Stone Age (McBrearty and Brooks 2000), the Mousterian industries of the Levant (e.g., Meignen and Bar-Yosef 1992), and the North African (e.g., Van Peer, 1998) and European Middle Paleolithic (e.g., Soressi 2005). The focus in this article was the relationship between cognition and stone tools, but this does not deny that technological choices in the Middle Stone Age and Middle Paleolithic and other time periods covary with ecology and subsistence. At Klasies River the techno-complexes seem to be broadly coeval with changes in climate. The climatic change associated with MIS 4, for example, has been used as a causal mechanism for the appearance and characteristics of the Howiesons Poort. Foraging theory has been used to interpret the change in raw material use in the Howiesons Poort as evidence for an increased mobility strategy (Ambrose and Lorenz, 1990) and/or as a social strategy for sharing information and reducing risk (Deacon 1989; Minichillo 2006). McCall (2007) also argues within the context of the behavioral ecology model that the Howiesons Poort represents a response to resource availability and the environment. Two points can be made in this regard. It can be questioned whether the available climatic reconstructions are of sufficient resolution (Jacobs et al. 2008) to trace how the environment affected human behaviors directly. Such hypotheses often reify lithic and raw material changes because they are based on secondary interpretation of published data sources with sometimes contradictory information.

A refreshing approach to analyze the thought processes involved in Paleolithic tool use has been followed by Wadley and colleagues (2009; Wynn 2009). They replicated compound adhesive used to haft Howiesons Poort backed artifacts from Sibudu Cave and inferred the "capacity for multilevel operations, abstract thought and mental rotation" typical of modern ways of thinking from the procedures followed. The other process involved in hafting may also have the potential to provide insights into cognitive evolution (Ambrose 2001). Hafting is a well-documented feature of Middle Paleolithic and Middle Stone Age assemblages (Lombard 2005; Rots and Van Peer 2006; Shea 2006; Villa and Lenoir 2006; Villa et al. 2009b). It is highly probable that the Howiesons Poort backed artifacts from Klasies River (Deacon 1989; Wurz and Lombard 2007), but also the blades and points of the MSA 1 and 11, were hafted. It is evident that different norms guided the choice of appropriate forms to haft since about 200,000 years ago. Different forms that included retouched and unretouched forms were selected as preferred projectiles through time.

Other classes of archaeological material culture that have been mentioned in relation to symbolic abilities in the Late Pleistocene Middle Stone Age of South

Africa are intentionally marked ostrich eggshell from Diepkloof (Parkington et al. 2005) and the engraved ochers (Henshilwood et al. 2002; Henshilwood, d'Errico, and Watts 2009) and the approximately 75,000-year-old beads (Henshilwood et al. 2004) from Blombos cave. One view, as for example put forward by Conard (2005, 2008), is that these artifacts may constitute innovations but not appropriate markers for symbolic cognition. More appropriate archaeological indicators of symbolic cognition may be figurative representation, three-dimensionally shaped ornaments rather than perforated natural objects, evidence of purposeful burial, therianthropic imagery that does not mimic the natural world and musical instruments. From this limited perspective, neither the early markers for symbolism in South Africa nor patterning in stone tools would be relevant to the development of theories on the evolution of symbolic capabilities. It remains a major challenge for Paleolithic archaeologists to identify and construct appropriate theory for the scientific investigation of modern symbolic cognition (Givón and Malle 2002). The variability in stone tools is a reflection of representational neuronal processes and therefore expecially relevant to the evolutionary theory of symbolic cognition.

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EIGHT

Possible Relations between Language and Technology in Human Evolution

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ABSTRACT

Complex tool use and language are distinguishing characteristics of the human species, yet the existence and nature of evolutionary relations between them remain controversial. Current thinking highlights three possible types of coevolutionary interaction involving shared neural substrates, shared social context, and shared reliance on general capacities. Evidence reviewed here supports the relevance of all three types of interaction and illustrates the contribution that detailed studies of archaeologically visible, technological behaviors, like stone knapping, can make to the study of human cognitive evolution. First, recent functional brain imaging studies of Lower Paleolithic tool making demonstrate an overlap with cortical language circuits that is consistent with motor hypotheses of speech and language origins. Second, ethnographic and developmental evidence highlights the role of joint attention and intentional communication in the social reproduction of both stone knapping and language skills. Finally, growing appreciation of the importance of hierarchical cognition—not simply in language but across domains of human action—is consistent with shared reliance on general information processing capacities.

INTRODUCTION

Complex tool use and language are distinguishing characteristics of the human species. For this reason alone, it is tempting to posit evolutionary connections between them. For archaeologists, the possibility that Paleolithic stone tools might shed light on language evolution is even more appealing. But are human language and tool use really related in any more meaningful way than that both are products of an expanded hominin brain (Hewes 1994)? Everyday experience does not suggest obvious links between the two. In fact, stereotypes like the bumbling professor or the hopelessly confusing some-assembly-required instruction manual suggest exactly the opposite. Archaeologists considering this question have similarly posited important differences between language and tool use, including the presence of innate and/or "domain specific" elements in language processing (Wynn 1993) and the absence of language-like syntax and semantics in tool use (Graves 1994). In this view, tool use and language are linked by nothing more specific than a few general cognitive abilities and the overarching context of cultural transmission (Graves 1994; Wynn 1993).

Along these lines, it is important to recognize that human language is a complex phenomenon, incorporating a wide array of sensorimotor, conceptual, and grammatical components. It remains controversial which of these might actually be unique to language (Hauser, Chomsky, and Fitch et al. 2002; Pinker and Jackendoff 2005); however, it is clear that many are shared with other behaviors. Working memory, for example, represents a likely point of overlap between language and tool use, insofar as both activities require the construction, production, and analysis of complex sequential action (Gibson 1999; Lieberman 2002; Wynn and Coolidge 2006).

Other potentially informative relations arise from the shared social context of human language and technology. Although the apparent innateness of human language acquisition has been cited as an important difference from tool use (Wynn 1993), the relative importance of innate capacities, heritable predispositions, environmental context, and social learning in each case has yet to be fully resolved (Lockman 2000; Pinker 1995; Tomasello 1995). Less controversial is the fact that social interaction plays at least some role in language acquisition, as well as in tool use and the acquisition of complex skills generally. For this reason, species that excel at tool use tend to be those that also possess rich social and communicative repertoires (Emery and Clayton 2004; Reader and Laland 2002). Formal modeling further indicates that selection for increased sociability and/or social learning ability is the most likely consequence of fitness benefits associated with the expression of complex skills (van Schaik and Pradhan 2003).

In humans, complex skill acquisition is facilitated by cultural learning (Tomasello, Kruger, and Ratner 1993) involving mental state attribution ("theory of mind") and joint attention. These are, of course, critical components of human linguistic communication in the broad sense (Hauser, Chomsky, and Fitch 2002) and central to the normal course of language acquisition (Carpenter et al. 1998). At the same time, language itself plays an important role in human technological learning and performance, providing a means of directing attention and action during shared activities (Reynolds 1993). This is particularly important in apprenticeship learning, where language can mediate aspects of meaning, motivation, and identity critical to the learning process (Lave and Wenger 1991; Rogoff 1990; Stout 2005).

But could tool use also have played a more direct role in language evolution? Motor hypotheses of language evolution (Greenfield 1991; Kimura 1979; Lieberman 1984; MacNeilage 1987; Rizzolatti and Arbib 1998) have variously proposed that speech, syntax, and semantics all have their origin in prior adaptations for motor coordination and/or object manipulation. Greenfield (1991) in particular has argued that language and object combination (including tool use and making) are constructive, hierarchically organized activities with a common developmental and evolutionary foundation in Broca's area of the left inferior frontal gyrus. More recently, this region of frontal cortex has also been identified as a major node in the mirror-neuron system of action understanding, a cortical network hypothesized to have provided a pre-adaptive substrate for intentional communication (Rizzolatti and Arbib 1998). Such work increasingly supports a direct evolutionary link between language and tool use.

Current thinking thus highlights three sets of possible relations between language and tool use in human evolution. Each implies a certain degree of coevolution and, importantly, makes predictions that are at least theoretically testable with respect to specific linguistic and technological behaviors. These possible relations are listed here.

1. Shared reliance on general capacities, such as working memory. This relationship implies coevolution in the sense that increases in these general capacities, for whatever reason, would tend to benefit both language and tool-using abilities. Its key prediction is that both linguistic behavior and Paleolithic technologies should be demanding of these general capacities.
2. Shared social context, including cognitive capacities for mental state attribution and joint attention, as well as the pragmatic contribution of language to complex skill learning and cooperative activity. This relationship implies coevolution in the sense that evolving language and tool-use capabilities would provide a complementary context for one another. Its key prediction

is that linguistic behavior and Paleolithic technologies should depend on similar cultural learning mechanisms for their reproduction.

3. Shared neural substrates underlying more specific aspects of language and tool use, including hierarchical combination in the inferior frontal gyrus and action understanding in the cortical mirror-neuron system. This relationship implies coevolution in the stronger sense that tool use would actually have provided a preadaptive foundation for specific aspects of the human language faculty. Its key prediction is that linguistic behavior and Paleolithic technologies should recruit overlapping neural substrates and processes.

These three possibilities are not mutually exclusive and each might be more applicable to some technological and linguistic behaviors than to others. For example, the manufacture of an Acheulian handaxe might be more demanding of working-memory capacity than is the production of Oldowan flakes, just as working memory might play a greater role in sentence parsing than in phonological processing.

In order to evaluate the actual evolutionary significance of these possible relations, it is necessary to test their predictions with reference to specific behaviors. Stone tool making is one such behavior that is archaeologically visible and exhibits a great time depth. The following sections draw on currently available evidence to examine the possible relations between stone tool making and language in human evolution, beginning with the strongest claims of specific neural and functional overlap.

SHARED NEURAL SUBSTRATES

Brain Activation during Oldowan Tool Making

Holloway (1969:404) provided an early examination of similarities between stone tool making and language, concluding that "selection favored the cognitive structures dependent on brain organization and social structure which resulted in both language and tool-making." More recently, Wynn (1993) suggested that the strongest link between tool behavior and language would come from evidence that the two "make use of the same neural structures or functions." In the same volume, Toth and Schick (1993) proposed that functional brain imaging might be used to look for precisely such points of overlap. This suggestion has now been implemented for Mode I (Oldowan-style) (Stout and Chaminade 2007; Stout et al. 2000) and Mode II (Acheulian-style) (Stout et al. 2008) stone knapping.

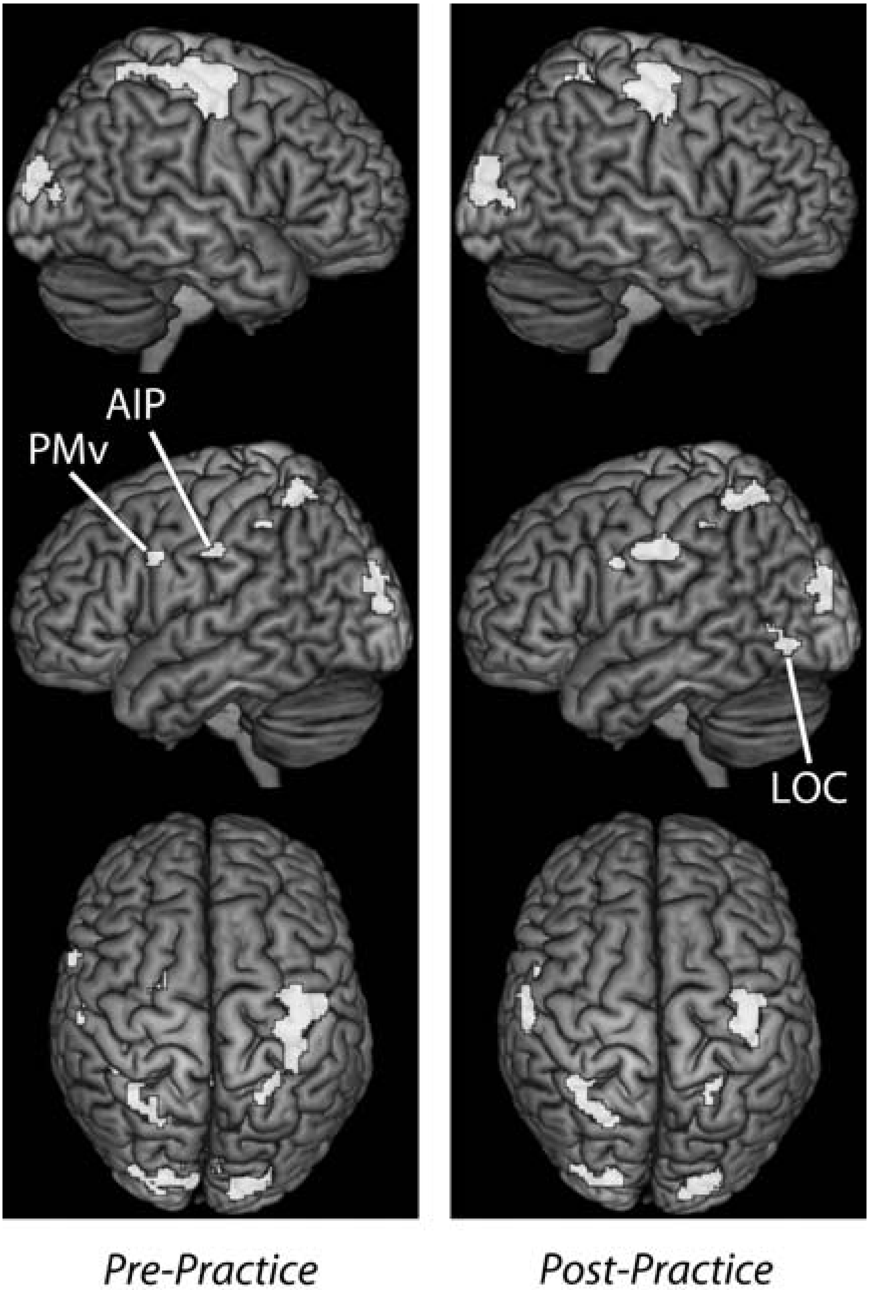
In one study (Stout and Chaminade 2007), positron emission tomography (PET) was used to collect brain activation data from six right-handed subjects producing Mode I flakes. Subjects had no prior knapping experience and were imaged both before and after four hours of practice. Data from these experimental knapping conditions were contrasted with a control condition in which subjects simply struck cobbles together without attempting to produce flakes. This allowed for the identification of activation specific to the requirements of flake production as opposed to more generic object manipulation and percussion.

Results from both naïve and practiced knapping conditions (Figure 8.1) indicate, among other things, increased activation of a parietofrontal action system including the anterior intraparietal sulcus (AIP) and ventral premotor cortex (PMv). These regions are homologous to cortical areas recruited during object prehension (Rizzolatti, Luppino, and Matelli 1998) and tool use (Obayashi et al. 2001) in monkeys, and their preferential recruitment during Mode I knapping thus indicates increased demands on an evolutionarily conserved cortical system that performs sensorimotor transformations for object manipulation (Maravita and Iriki 2004; Rizzolatti, Luppino, and Matelli 1998). This is particularly interesting for the current investigation because PMv, located directly adjacent to Broca's area, is a major locus of potential overlap with language processing.

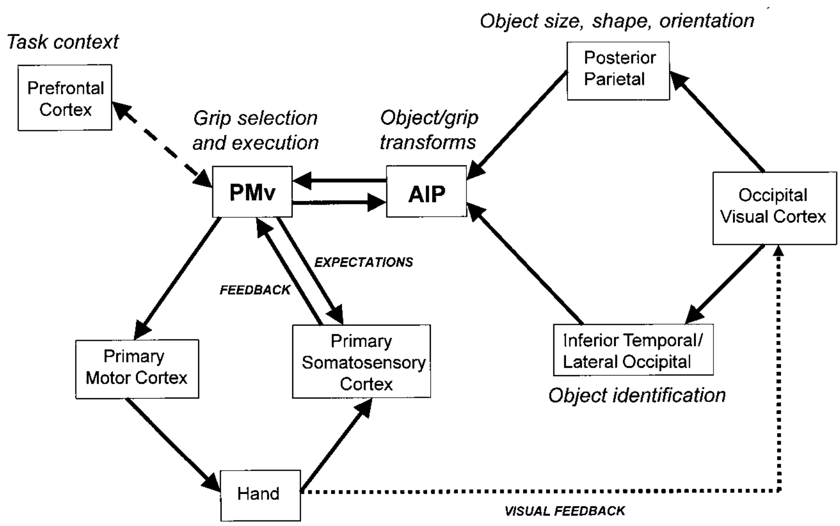
Shared Neural Functions in Language and Tool Making

Effective tool use, including tool making, requires dexterous manual prehension. This in turn requires the transformation of sensory information about object shape into appropriate grasping configurations of the hand (Frey et al. 2005). As in macaques (Rizzolatti, Luppino, and Matelli 1998), the human AIP is a visual-motor association area that plays a critical role in visually guided grasping (Frey et al. 2005) by providing information about object affordances to the PMv. According to the Fagg-Arbib-Rizzolatti-Sakata (FARS) computational model of grasping, in AIP-PMv (Figure 8.2) (Fagg and Arbib 1998) visual information presented to the AIP is used to derive a set of potential grasps; these grasps are passed to the PMv, which selects among them on the basis of additional constraints such as task goals; this decision is communicated back to the AIP, which shunts the non-selected grasp affordances; and the PMv is then responsible for the execution of the selected grasp as a sequence of functionally unified action components (e.g., extension, flexion, hold, release).

This specific model is consistent with a more general computational account of motor control known as HMOSAIC (Hierarchical Modular Selection and Identification for Control) (Haruno, Wolpert, and Kawato 2003). In simple MOSAIC (Wolpert and Kawato 1998), the sensorimotor system achieves consistent performance across variable environmental conditions by generating and



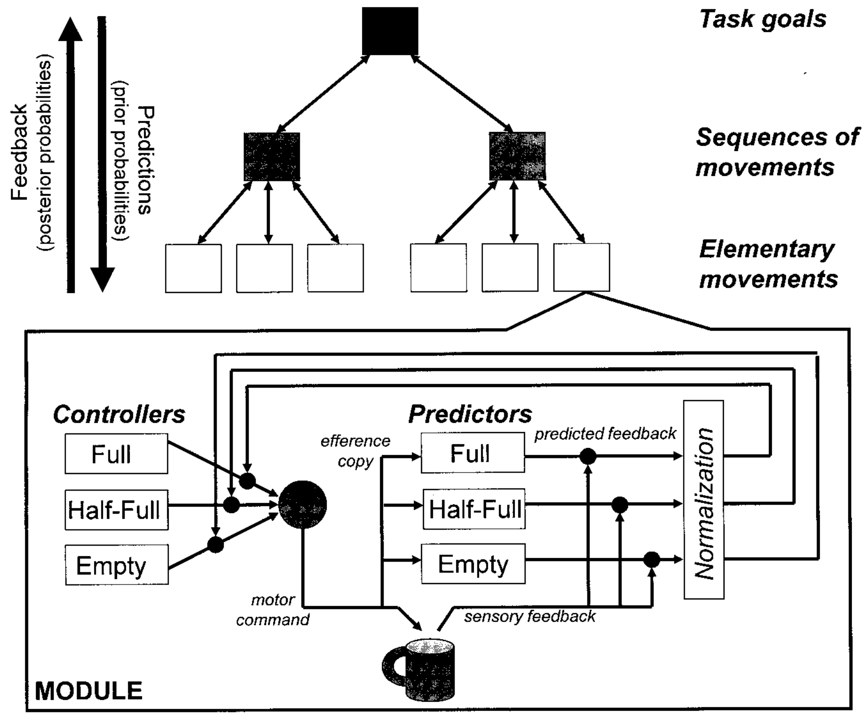
8.1. Brain activation during naïve and practiced Oldowan knapping by novices. Note activation of the AIP-PMv circuit in both conditions and enhanced activation of visual association cortex (LOC) following practice.



8.2. The Fagg-Arbib-Rizzolatti-Sakata (FARS) computational model of grasping in AIP-PMv (drawn after Fagg and Arbib 1998).

selecting among multiple motor plans on the basis of sensory feedback. More specifically, motor plans ("controllers") are used to make sensory predictions that are tested against actual feedback (Figure 8.3, lower part). In this way, rapid adaptation is achieved. However, actual motor behavior also displays higher-level regularities relating to conserved motor sequences and overall task goals. For example, most people can write a recognizable letter *A* with various different pens, with their left or right hands, or even by grasping the pen between their toes (Manoel and Connolly 1995).

HMOSAIC accounts for this consistency across conditions by employing multiple, interacting levels of predictor-controller pairings ("modules") corresponding to increasingly abstract aspects of the behavior (e.g., elementary movements, sequences of movements, goals of sequences). Higher levels generate predictions (Bayesian prior probabilities) used to prioritize module selection at lower levels, which return feedback (posterior probabilities) on outcomes to the higher levels. This hierarchical architecture (Figure 8.3, upper part) combines bottom-up and top-down processing in a way that allows HMOSAIC to learn both elementary movements and their higher-level sequencing through sensorimotor learning (Wolpert, Doya, and Kawato 2003).



8.3. The HMOSAIC (Hierarchical Modular Selection and Identification for Control) model of motor control (drawn after Wolpert et al. 2003). Efferent prediction and sensory feedback are used to select appropriate motor commands in low-level modules controlling elementary movements. These elementary movements are assembled into coherent sequences and adaptive, goal-oriented behavior through a combination of top-down and bottom-up processing. The production of hierarchically organized sequences in this model is formally similar to that required in language processing.

Following two these models, the role of the PMv in grasping may be described as the selection and sequential unification of action components with respect to object affordances provided by AIP and higher-level representations of task context and goals provided by the prefrontal cortex (Fagg and Arbib 1998). This form of hierarchical processing, involving the selection and unification of discrete elements to produce coherent higher-level structures, bears intriguing similarities to recent accounts of language processing based on the recursive combination of lexical elements through selection acting on intrinsic structural features (Jackendoff 2002; Vosse and Kempen 2000).

In these accounts, traditional distinctions between combinatorial rules (grammar) and lexical elements (the lexicon) are largely eliminated (Bates and

Goodman 1997) in favor of a single process of unification acting on content-rich lexical items containing information about their own combinatorial possibilities. Similar processes of unification have been hypothesized to operate throughout the tripartite structure (phonology, syntax, and semantics) of human language (Hagoort 2005). As in both FARS and HMOSAIC, competition and selection between elements provide the proposed mechanisms for unification. For example, the use of lateral inhibition between competing unification links to generate a single, successful syntactic tree, as proposed by Vosse and Kempen (2000), may be explicitly compared with the use of inhibitory connections in FARS to ensure the emergence of a single, adaptive grasp.

Neuroanatomical Overlap

But does this computational similarity indicate a true evolutionary homology between object manipulation and linguistic processing or merely an interesting analogy (Wynn 1993)? After all, recursion and selection are powerful general mechanisms that might easily be used by many different cognitive systems. Additional support for a homology would come from evidence that PMv is in fact recruited for both tool making and language functions. This does appear to be the case. At least one recent review (Hagoort 2005) has concluded that anterior PMv plays a role in unification during phonological processing; this is the location, near the posterior border of Brodmann area 44 (classic Broca's area), that is activated during Mode I tool making.

The functionality of any brain region is largely determined by its pattern of connections with other brain regions (Passingham, Stephan, and Kotter 2002). Anterior PMv in particular is a major point of convergence for inputs from parietal sensory association cortices (Rizzolatti, Luppino, and Matelli 1998) and prefrontal area 46 (Takada et al. 2004). In turn, it sends outputs via the more posterior PMv to the manual and orofacial regions of the primary motor cortex (Takada et al. 2004). Consequently, it plays a key role in multiple neural circuits supporting sensorimotor transformations for action across a variety of modalities. Macaque PMv, for example, displays overlapping responsiveness to visual, tactile, and auditory stimuli (Graziano, Reiss, and Gross 1999) and has recently been found to coactivate with the perisylvian auditory cortex (a putative Wernicke's area homologue) in the perception of species-specific calls (Gil-da-Costa et al. 2006). In humans, the PMv is loosely divided into inferior and superior fields, which are responsive to auditory and visual stimuli, respectively (Schubotz and von Cramon 2003). This division, which mirrors the superior/inferior organization of hand and orofacial regions in the primary motor cortex, is also evident during action observation, with the superior PMv field responding to observed hand actions and the inferior portion to observed mouth actions (Buccino et al. 2001).

Although the extent of functional overlap between PMv fields is not well-known from imaging data, behavioral evidence indicates close interaction. One obvious example is the interdependence (Rauscher, Krauss, and Chen 1996) of manual gestures and speech in human communication (McNeill 1992). This relationship is present even in congenitally blind speakers talking to blind listeners (Iverson and Goldin-Meadow 2001). Kinematic studies have further demonstrated that grasping movements with the hand affect concurrent movements of the mouth, with larger manual target objects being associated with wider, faster opening of the mouth and with increased power of the voice spectrum during syllable pronunciation (Gentilucci et al. 2001). Finally, it seems that manual and oral control are even less well-differentiated during development, as exemplified by the Babkin reflex of newborns in which pressure to the palm results in mouth opening (Babkin 1960).

These observations are broadly consistent with the evolutionary-developmental hypothesis of Greenfield (1991), who proposed that discrete manual and linguistic circuits in the posterior inferior frontal lobe emerge through postnatal developmental differentiation of a common neural substrate. Such differentiation is thought to result from the exuberant growth and subsequent pruning of synaptic connections, driven by neuronal competition, intrinsic gene expression gradients, and extrinsic stimuli (Deacon 1997; Edelman 1987). In the case of the PMv, these processes would be expected to result in the differentiation of multiple neuronal populations playing similar roles in different neural circuits. The overt functional characteristics of these partially overlapping populations would then be a function of their particular patterns of connectivity with other (sensory, cognitive, and motor) brain regions.

Greenfield (1991) further argues that linguistic grammar and manual object combination in particular are homologous expressions of the hierarchical information-processing capabilities of Broca's area. The evidence of functional and anatomical overlap discussed above does support such a link between phonological processing and elementary object-oriented actions (e.g., grasping) but does not extend to the more complex multi-object and grammatical combinations ultimately invoked by Greenfield's hypothesis. The units of analysis involved are thus closer to those employed in scenarios linking manual specialization to speech production (Kimura 1979; Lieberman 1991; MacNeilage 1987), although Greenfield's more general argument regarding the developmentally differentiated hierarchical unification functions of inferior frontal cortex is clearly corroborated. In fact, more recent investigations (Stout et al. 2008) have shown more anterior activation of the right hemisphere homolog of Broca's area during Mode II tool making. This activation during more sophisticated tool making is perhaps unsurprising considering that a posterior-to-anterior gradient of phonological, syntactical, and semantic processing clearly exists in the linguistic functions of the inferior frontal cortex (Bookheimer 2002; Hagoort 2005) and that a similar gradient appears to be present for increasingly abstract levels of action observation (Nelissen et al. 2005). In any case, it provides further corroboration for Greenfield's hypothesis.

The Mirror-Neuron System

Another major reason for interest in PMv activation during Oldowan tool making is the role this region plays in the mirror-neuron system for action understanding. Mirror neurons, initially identified in the premotor cortex (area F5) of macaques (Di Pellegrino et al. 1992; Gallese et al. 1996; Rizzolatti et al. 1996), are a special class of visuomotor neurons that discharge both during the execution of a particular action and during the observation of a similar action being performed by another individual (Rizzolatti and Craighero 2004). These highly specific response characteristics indicate that neural networks involved in the execution of actions are also spontaneously recruited by their observation. This automatic internal simulation of observed actions in the mirror-neuron system is thought to constitute a neural mechanism for recognizing the action goals and intentions of others (Fogassi et al. 2005; Rizzolatti and Craighero 2004) and has led to the hypothesis that mirror neurons provided a preadaptive foundation for understanding intentional communicative gestures (Rizzolatti and Arbib 1998).

Necessary differences in research methods make it impossible to record from individual mirror neurons in human subjects; however, noninvasive imaging has amply demonstrated overlap between action observation and execution in the inferior frontal/precentral gyrus (i.e., Broca's area / PMv) and the anterior part of the inferior parietal lobe (Rizzolatti and Craighero 2004). This corresponds closely with known locations of mirror neurons in macaques (Di Pellegrino et al. 1992; Fogassi et al. 2005) and is strongly suggestive of homology. Interestingly enough, these regions also show some degree of overlap with language processing (Hamzei et al. 2003, and above).

Of course, macaques do not speak, so the really interesting question with respect to language evolution is how the human mirror system might differ from that of monkeys (and other apes, although such comparative evidence is lacking). For example, whereas the responsiveness of monkey mirror neurons is specifically limited to transitive (object-directed) actions, transcranial magnetic stimulation (TMS) and magnetic resonance imaging research indicate that the human mirror-neuron system is also responsive to intransitive finger flexion (Patuzzo, Fiaschi, and Manganotti 2003) and to pantomimed actions toward imaginary objects (Buccino et al. 2001). This apparent broadening of response characteristics is consistent with the hypothesis that derived characteristics of the human mirror neuron might support intentional communication (Rizzolatti and Craighero 2004), although further research is clearly needed. This is also the case with TMS studies suggesting a similar "echo-neuron" system for human speech perception (Fadiga et al. 2002; Watkins, Strafella, and Paus 2003).

PMv activation during Oldowan tool making is located in left anterior Brodmann area 6, bordering area 44, in a region that has been identified as homologous to monkey area F5 (where mirror neurons are found) on the basis of sulcal anatomy (Rizzolatti, Luppino, and Matelli 1998), quantitative architectonics and electrophysiological response characteristics (Petrides, Cadoret, and Mackey 2005). This approximate location has also been identified as a point of overlap among action observation, action execution, and language production in humans (Hamzei et al. 2003). This suggests that elements of the mirror-neuron system may be preferentially recruited by Oldowan knapping as compared to simple percussion. However, this hypothesis has yet to be directly tested by experiments involving knapping action observation.

Potential Evolutionary Implications of Knapping-Related Brain Activation

Functional imaging studies with modern humans cannot directly reveal the mental capacities of prehuman ancestors but can shed light on the relative demands of evolutionarily significant tasks. For example, activation of the AIP-PMv circuit during Mode I knapping indicates that this technology is more demanding of sensorimotor transformations for object manipulation than is bimanual percussion without flake production. This most likely reflects the importance of deploying effective grips for hammer and core that expose the desired impact surfaces at an appropriate angle, provide sufficient support to absorb a powerful impact, and place fingers close to the point of impact in order to absorb shock and provide a kinesthetic guide for percussion (e.g., Stout 2002:698–699).

Although many animals combine objects for percussion (Marchant and McGrew 2005), only hominins seem capable (cf. Schick et al. 1999) of the control necessary for the efficient flake production seen at early Oldowan sites (Delagnes and Roche 2005; de la Torre 2004; Semaw 2000). In this context, comparisons of knapping with simple percussion bring into relief the truly distinctive neurobehavioral characteristics of stone tool making and highlight those brain regions most likely to have been relevant to evolving tool-making capacities. More specifically, functional and anatomical overlap between Oldowan knapping and phonological processing in the anterior PMv suggests that selection on tool-making abilities could also have contributed to an evolving hominin language capacity.

The relationship between size and function of cortical areas is not well-understood; however, one plausible outcome of selection acting on PMv functions involved in tool making would be expansion of this area. In fact, the premotor cortex as a whole does seem to be expanded in humans (Blinkov and Glezer 1968), although not to the same extent as prefrontal and temporo-parietal association cortices (Deacon 1997; Rilling 2006). The KNM-ER 1470 endocast from Koobi Fora, Kenya, provides direct evidence of a more complex and modern-human-like Broca's area (i.e., third convolution of the inferior frontal gyrus) dating back approximately 1.9 million years (Holloway 1999), although PMv itself cannot be resolved.

Many such characteristics of human neocortical organization may simply reflect the effects of extended development (Finlay and Darlington 1995), allometric expansion, and resulting design constraints (Deacon 1997). Nevertheless, comparative studies also document substantial residual variability suggestive of species-specific adaptation (Rilling 2006). Such adaptations, in the PMv or elsewhere, would necessarily be driven by changes in the more proximate mechanisms governing the formation of functional areas within the developing cortical plate.

Researchers are only now beginning to understand this process of cortical arealization, which appears to be regulated in large part by the influence of axonal projections from the thalamus. These axons, originating in the sensory nuclei of the dorsal thalamus, are a major source of sensory input throughout the neocortex and play an important role in inducing anatomical and functional differentiation (O'Leary and Nakagawa 2002). These projections are in turn guided by a combination of extrinsic neural stimulation and intrinsic chemical gradients produced by regional variations in gene expression (O'Leary and Nakagawa 2002). These mechanisms provide a large degree of plasticity. For example, the relatively common evolutionary phenomena of gene duplication might easily alter the expression of intrinsic gradients in such a way as to produce a real expansion or contraction (Deacon 1997). Alternatively, changes in neural stimulation derived from other cortical, subcortical, or somatic sources might alter neuronal survivorship during development, resulting in a net size increase or decrease. This latter process is referred to as displacement by Deacon (1997).

The potential for interaction between these mechanisms also suggests possible knock-on effects of PMv expansion. For example, gene duplication resulting in an expanded premotor cortex would increase the number of potential connections to and from the PMv during development and provide new raw material for displacement. Expanded neuronal populations in PMv might thus be recruited by various different circuits in a relatively plastic fashion. Interestingly enough, it has recently been shown that tool-use training leads to the extension of new functional connections from the visual and prefrontal cortex to the anterior intraparietal sulcus of adult macaques (Hihara et al. 2006). Comparable plasticity in an evolving speech circuit involving auditory, ventral premotor, and orofacial motor cortex would provide a potential mechanism for Baldwinian evolution (Deacon 1997) through genetic assimilation (Waddington 1953). In this way, behavioral changes that increased the fitness benefits of intentional vocal communication could lead to the developmental canalization of previously plastic responses, helping to produce the enhanced articulatory control so central to human language evolution (Deacon 1997; Lieberman 2002; MacNeilage 1995; Studdert-Kennedy and Goldstein 2003). One major candidate for such behavioral change is increasing reliance on the social learning of complex skills, including stone tool making (Stout 2005).

SHARED SOCIAL CONTEXT

Technical skill acquisition (Stout 2002, 2005) and collaborative performance (Reynolds 1993) are far from being the only behavioral contexts that might have favored intentional vocal communication in hominin evolution and may not even be the most important (Dunbar 1996). However, technological performance is the only context for which a substantial body of direct paleo-behavioral evidence currently exists. Happily, such performance does have the potential to be a rich source of information about social and communicative capabilities.

It has been argued that vocal communication is relatively unimportant relative to physical demonstration in the transmission of tool-making skills (e.g., Dunbar 2003); however, this is a narrow view that neglects the importance of intentional vocalization in directing attention during joint action (including pedagogy) and of language generally in establishing the social context for technological reproduction. In fact, a strict division between the technological and the social appears untenable in both human (e.g., Dobres 2000) and nonhuman (van Schaik et al. 2003) primates. Dunbar (2003) has proposed that the selection on the social cohesive functions of language preceded any eventual technological benefits; however, this becomes a bit of a chicken-and-egg problem when it is recognized that facilitation of the social reproduction of technical skills was likely to have been an important factor favoring the formation of larger and more cohesive groups in the first place (van Schaik and Pradhan 2003).

Stone knapping in particular is distinguished from other manual activities by its requirements for combined force and accuracy of percussion. Experimental and ethnographic studies (Bril, Roux, and Dietrich 2000; Roux, Bril, and Dietrich 1995; Roux and David 2005; Stout 2002) have shown that mastery of elementary flake removal is a necessary precondition for the emergence of structured and effective knapping strategies and that sufficient perceptual-motor skill is only achieved through dedicated practice over a prolonged period—often years. Knapping experiments (Stout and Chaminade 2007) corroborate these observations and show that, even in Mode I tool making, novice performance is highly constrained by the difficulty of combining force and accuracy in percussion. Four hours of practice were sufficient for subjects to advance from uncontrolled fracture to the preferential exploitation of favorable knapping surfaces, realized through small, marginal flake removals from acute platforms. This strategy minimized demands for force and accuracy in percussion but led to edge rounding, low productivity, and premature core exhaustion.

Interestingly enough, this strategic shift was accompanied by increased activation of visual association areas (the lateral occipital complex [LOC] and intraparietal transverse occipital [IPTO]) involved in object recognition and visual search, most likely relating to increased attention to technologically relevant aspects of core morphology but not with any modulation of prefrontal activity, which might suggest increased demands for motor planning and problem solving (e.g., Dagher et al. 1999). This is contrary to the pattern seen in the acquisition of less demanding motor skills, such as figure tracing and sequential button pressing, in which initial learning of task strategy / organization is "scaffolded" by activation in prefrontal and posterior parietal association cortices before shifting to more automatic execution in primary sensorimotor cortices (Kelly and Garavan 2005). These observations further emphasize the unusual perceptual and motor demands of stone knapping and illustrate the bottom-up emergence, rather than top-down imposition, of strategic regularities during skill acquisition (see also Roux and David 2005). More recent core-shaping, prepared-core, and blade technologies are clearly even more demanding of acquired perceptual-motor skill, although detailed experiments are required to quantify these differences.

Trends toward increasing skill and refinement evident in the archaeological record of the past 2.5 million years thus provide evidence of increasing investments in perceptual-motor skill acquisition. In modern humans, such investments

8.4. A traditional stone tool-making apprenticeship situation in Langda, New Guinea. Vocal and gestural instruction combine to provide "coaching" that dramatically reduces the trial and error involved in skill acquisition.

are supported by social and cultural structures that both support and motivate deliberate practice. For example, among modern stone adze makers in the New Guinea village of Langda, learners participate in a semiformal system of apprenticeship that provides opportunities for instruction, observation, and assisted action (i.e., social "scaffolding"), as well as motivation related to economics, prestige, and identity (Stout 2002, 2005). Linguistic communication plays a key role in this system of apprenticeship by facilitating joint action and the cultural construction of identity.

During interactions between novice and expert knappers, gesture (usually pointing) and vocalization are frequently combined to convey meaning and shape behavior (Figure 8.4). Common utterances include phrases like "do it here," "don't do that," "look here," or "wait, you have to do this [e.g., hit this side] first," which serve to direct attention to important aspects of action that might otherwise be quite difficult for novices to discern. This enables a form of coaching that can dramatically reduce the trial and error involved in skill acquisition. Although such linguistic utterances may not be strictly essential to the cultural reproduction of knapping skills, it is nevertheless clear that they greatly facilitate communication and learning by modifying or adding to the meaning of accompanying gestures. Language also plays a more fundamental role in establishing the cultural context that supports skill learning in Langda. This includes linguistically constructed kinship ties that cement relations between teachers and learners; myths, stories, and specialist terminology that create craft identity and a sense of belonging; and even the small talk, gossip, and joking that makes knapping an enjoyable social activity. In other words, language provides a social glue (Dunbar 1996) holding together the structures that support the reproduction of complex knapping skills. For these reasons, increased reliance on complex, socially facilitated skill learning over the course of hominin evolution would be likely to increase fitness benefits associated with intentional vocalization and (proto)linguistic communication.

Socially facilitated technical skill learning might also plausibly contribute to the preadaptive context of language evolution, insofar as learning in both domains is supported by capacities for joint attention. The kind of coaching and interactive skill learning described above clearly rely on shared attention to particular task features and a causal / intentional understanding of both technical and communicative actions. This is consistent with a substantial body of work detailing the importance of joint attention, scaffolding, and "cognitive apprenticeship" in human learning generally (e.g., Lave and Wenger 1991; Rogoff 1990; Wood, Bruner, and Ross 1976). This same ability to focus on objects and events being attended to or indicated by adults is critical to language learning, and joint attention skills have in fact been shown to correlate with individual variation in the development of both language and gesture (Bates and Dick 2002; Carpenter et al. 1998). At this basic level, linguistic and technological behaviors do appear reliant on similar cognitive mechanisms supporting social reproduction. Currently available evidence certainly does not put us in a position to associate a particular prehistoric technology with a specific level of linguistic or proto-linguistic communication and such a level of interpretation may never be possible. Nevertheless, there are important links between technology and communication in human evolution that may be expected to reward further investigation.

GENERAL CAPACITIES

One point that emerges from the earlier comparison of the neural substrates of language and tool making is that both rely on hierarchical unification functions of the inferior frontal cortex. The observed overlap in Mode I knapping is specific to manual coordination and articulatory / phonological processing; however, putative involvement of more anterior regions in more complex tool making would involve increasingly abstracted, domain-general unification processes.

This latter possibility is quite similar to the idea advanced by Gibson (1993) that distinctive human abilities across a wide range of behaviors reflect quantitatively enhanced information-processing capacities, particularly the ability to hold multiple items of information in mind simultaneously and to assemble these items into hierarchical mental constructs (Gibson 1999).

Such domain-general processing, not tied to specific sensory or motor modalities, is generally considered to be the province of association areas in the prefrontal, posterior parietal, and temporal cortex. These association areas are, in fact, among the most expanded regions of the human neocortex (Rilling 2006) for reasons that may include developmental timing, patterns of connectivity, neural design constraints, and/or specific behavioral adaptations. Involvement of these regions in complex stone tool making would not necessarily indicate a special relationship between language and technology in human evolution but would be consistent with the proposal of a more generalized human "cognitive niche" involving closely interdependent social, technological, and linguistic components (Gibson 1993). More specifically, it would provide support for the argument that archaeological traces of complex tool making can provide circumstantial evidence of comparable advances in social and linguistic behavior (Gibson 1993).

Both working memory (the ability to hold multiple items in mind) and hierarchical unification are typically associated with the prefrontal association cortex. As we have already seen, the anterior inferior frontal gyrus appears to be centrally involved in high-order unification operations across modalities (Hagoort 2005). Working memory is classically associated with more dorsal regions of the prefrontal cortex, and its behavioral expression is now thought to involve a combination of online storage in Brodmann area 8 and response selection in area 46 (Rowe et al. 2000). Along these lines, Dagher and colleagues (1999) found that dorsolateral prefrontal activation, including area 46, increased in proportion to the complexity (i.e., number of moves required) of the classic Tower of London motor-planning task.

No such prefrontal activation was observed during novice Mode I tool making, either before or after practice. This may reflect the relative simplicity of Mode I flaking or simply the fact that novice subjects never mastered elementary flake removal and were thus unable to pursue the kind of systematic and intensive reduction seen at early archaeological sites (see, e.g., Delagnes and Roche 2005; Semaw 2000). Expert Mode II tool making did result in inferior prefrontal activation (Stout et al. 2008), consistent with the greater hierarchical complexity of the action sequences involved, but again did not recruit more dorsal regions classically associated with working-memory storage.

CONCLUSIONS

A steadily growing body of evidence indicates the likelihood of important interrelationships between language and technology in human evolution on levels ranging from specific neural overlap to the broader cultural context of learning and practice. Closer study of specific, archaeologically visible technological behaviors, such as stone knapping, offers the opportunity to further specify these possible relations, to test their applicability in particular cases, and to relate these findings to the chronological and contextual information (Wynn 2002) provided by the archaeological record of human behavioral evolution.

In the particular case of novice Mode I knapping, functional imaging data indicate an overlap with phonological/articulatory processing in the left anterior PMv. This is consistent with various motor hypotheses of speech evolution (Kimura 1979; Lieberman 1991; MacNeilage 1987; Studdert-Kennedy and Goldstein 2003), as well as Greenfield's (1991) evolutionary-developmental scenario of language origins rooted in the manual combinatorial functions of the inferior frontal cortex. Together with recent evidence of functional/connectional reorganization in macaque monkeys following tool-use training (Hihara et al. 2006), these findings suggest that neural adaptations relating to tool-making skill could have provided a preadaptive foundation for the later evolution of cortical speech circuits through a process of developmental canalization (Waddington 1953).

This logic applies to both the production and comprehension of speech, capacities that appear to rely on an overlapping system of "echo-neurons" (Fadiga et al. 2002; Watkins, Strafella, and Paus 2003) comparable to the mirror-neuron system involved in visuomotor action understanding. Expansion of the response characteristics of this mirror-neuron system to include intransitive and pantomimed actions differentiates humans from macaques and may represent an important innovation in the evolution of intentional communication (Rizzolatti and Craighero 2004). Such attempts to explain the evolution of speech from mimetic precursors in the mirror-neuron system typically invoke an intervening phase of communication through referential brachiomanual gestures (Rizzolatti and Arbib 1998). However, a discrete gestural communication stage involving some form of proto–sign language may not be strictly necessary, insofar as intentional "coaching" during the acquisition of technological skills already provides a context for the association of vocalizations with referential manual gestures and pantomimes (cf. Rizzolatti and Arbib 1998). Ethnographic evidence (Stout 2002, 2005) in particular highlights the role of joint attention and intentional communication in the social reproduction of stone-knapping skills.

These capacities also play a critical role in modern human language acquisition (Bates and Dick 2002; Carpenter et al. 1998), and their elaboration during hominin evolution is likely to have been important in the emergence of novel social, technological, and linguistic behaviors. Although high-level human performance in these domains probably reflects the enhanced information-processing capacities of expanded neocortical association areas (Gibson 1993), initial adaptations may have been more affective than cognitive. In canids, for example, selection for docility and reduced emotional reactivity (i.e., domestication) is associated with enhanced social skills, including gaze following and response to referential gestures (pointing) (Hare and Tomasello 2005). Enhanced social tolerance further creates opportunities for collaborative action (see, e.g., Hare et al. 2007) and the social reproduction of skills (van Schaik and Pradhan 2003), potentially increasing the fitness benefits associated with intentional communication. In this way, distinctive human social, technological, and linguistic capacities may have their root in a form of "self-domestication" involving selection for reduced emotional reactivity to conspecifics (Hare et al. 2007). This seems particularly applicable to stone knapping, insofar as both ethnographic and experimental evidence indicate the need for relatively prolonged periods of deliberate practice in a supportive social context in order to develop the requisite perceptual-motor skills.

Functional brain imaging results from novice Mode I knappers (Stout and Chaminade 2007) shed additional light on the importance of deliberate practice and perceptual-motor learning in stone-knapping skill acquisition. Contrary to expectations from studies of skill acquisition in less challenging motor tasks, Mode I novices showed a pattern of increased activation in high-order visual association cortices following practice but no significant modulation of prefrontal activity. These findings, in conjunction with lithic evidence of a shift to controlled but noninvasive flaking following the practice period, suggest that the early stages of stone-knapping skill acquisition are devoted to exploring the perceptual-motor affordances of the task and to developing effective motor synergies for elementary flake detachment (Bril, Roux, and Dietrich 2000, Roux, Bril, and Dietrich 1995). It is only following the stabilization of these fundamental skills that it becomes possible to organize methodical and intensive core reduction of the kind seen at early Oldowan sites (Delagnes and Roche 2005; Semaw 2000) or the sequentially contingent knapping plans evident in later bifacial and prepared-core technologies. In such technologies, more anterior regions of the inferior frontal gyrus (Brodmann area 45) are in fact activated. This region of prefrontal cortex is known to be involved in syntactic and semantic levels of language processing, suggesting further possible links between language and technology in human evolution.

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NINE

Stone Tools and the Evolution of Hominin and Human Cognition

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ABSTRACT

In this chapter, I summarize some previously published work on the significance of the earliest stone tools in comparison with chimpanzee tool making and use. I then put that into the context of some theorizing about human cognition and its implications for understanding the evolution of hominin and human cognition. I then conclude with an extended discussion of the standard story of changes in stone-artifact making and use in the context of other recent theorizing about the evolution of language. I conclude that stone tools can be interpreted to give strong evidence about the evolution of cognition, but the outcomes depend on careful assessment of the theoretical basis for the argument.

RELATING COGNITIVE ABILITIES TO THE PRODUCTION OF STONE TOOLS

My present approach to stone tools and cognition was developed in 2003 during a research project titled Precursors to Culture at the Collegium Budapest led by Richard Byrne. Byrne has recorded the sequence of actions routinely engaged in, in the wild, by a gorilla he called Flossie to avoid the painful sting of nettle leaves as she ate them. As a matter of routine during the process of removing leaves from a stem and eating them, she folds the leaves over themselves to conceal the stings and she does so with precise individual movements and repetition of the sequence of movements (Byrne 2003). Byrne showed in his analysis that this sequence of actions is, to all intents and purposes, a *chaîne opératoire* for eating nettle leaves.

In another paper, Byrne (2004) emphasized various aspects of making stone tools: precision handling, accurate aiming, bimanual role differentiation, regular and sequential planning, hierarchical organization with subroutines, corrective guidance by anticipatory schema, high individual manual laterality, and population right-handedness. In his comparison between ape abilities, as exemplified by Flossie, and those exhibited by early stone industries, Byrne concluded that the dominant difference was in the accurate aiming of powerful blows as a requirement for making stone tools.

Particularly if we have been pelted with feces by chimpanzees at a zoo, we may not think of accurate aiming as a particularly human behavior or as a phenomenon that cries out to be labeled "cognitive," but there is a good case that it is both. First, it is not clear that the chimpanzee pelting is either accurate or precise (Osvath 2009), given the inevitability that we only notice it when we are struck (and the likely reluctance of granting bodies to fund the investigation of feces throwing). Second, in addition to Byrne's arguments, Calvin (1983, 1993) has shown that accurate throwing could provide a selective context for increase in neuron numbers in precisely that part of the brain where motor control of musculature is also associated with speech production. But this selective context only occurs in situations where the hominin can conceive of the task for which accurate aiming of powerful blows is advantageous—as in throwing something at prey or predator or in the "controlled throwing" that constitutes knapping stone to remove flakes. This argument would hold, whatever one thinks of Calvin's other suggestion, that Acheulian handaxes were made for throwing.

Beginning from this point, while in Budapest, Bill McGrew and I compared hominin stone tools and chimpanzee tool use to see which features of early stone tool working were indeed similar and which were different (Davidson and McGrew 2005). Our paper was principally concerned with moving beyond those arguments that had identified chimpanzee cultures (Whiten et al. 1999, 2001). We were motivated by my view that we can understand nothing about hominin and human evolution simply by identifying similarities between chimpanzee and human behavior. When we analyzed the evidence in a number of characteris-

Table 9.1. Comparison between stone tool use among earliest hominins and chimpanzees, expanded from Davidson and McGrew (2005:table 1).

	Hominins and humans	*Chimpanzees*
Procurement: raw material and hammerstone	Yes	Yes
Procurement: raw material	Yes	Maybe not
Production (and abandonment) of stone artifacts	Yes: cores, debitage, and useful flake tools	Probably not: broken hammers and flakes not perceived as tools
Learning	Yes	Yes
Carrying: hammer	Yes	Yes
Carrying: made artifact	Yes for flakes but not necessarily for cores	No
Use 1: what sorts of objects	Yes: hammers, cores, and flakes	Yes: but only hammers and anvils
Use 2: Pounding	Yes	Yes
Use 3: Cutting	Yes	No
Abandonment: useable persisting physical product	Yes: cores and debitage	No
Abandonment: useless products	Yes: and these persist	Yes: but these decay

tic stages of tool use, from procurement to abandonment, we found that there were differences (Table 9.1).

We began with a sequence of stages in the procurement of raw material, making and use of flaked artifacts, followed by their abandonment. When we compared the hominin and chimpanzee sequences, there were several differences, not all of which could be explained as being a result of lack of data collection among chimpanzees.

We emphasized two features of these differences, namely, that cutting was a significant innovation among hominins, and that the abandonment of stone-flaking debris created a new environment of opportunity for hominins. The first point is often overlooked at least in part because, despite the fact that they have not been seen to cut things in the wild, chimpanzees, bonobos, and orangutans can quite easily learn to cut, particularly in experiments when a reward is obtained by cutting a cord to open a feeding box (Wright 1972). This was the paradigm used in the experiments in stone tool making and use by the bonobos Kanzi and Panbanisha (Schick et al. 1999; Toth et al. 1993). But this simply means that apes can learn from humans in the appropriate circumstances, something that was already known from other behaviors. The discovery that sharp stones can be used to cut either plants or animal carcasses opened a new niche for hominins that went beyond that which was possibly through the use of teeth for similar but more limited purposes.

As regards the second point, the cores and abandoned flakes could be a new resource for making or obtaining new tools. Although the actions of chimpanzees leave material products, they are either the tools that can no longer be used or debris from the making of the tools, which have no real or potential function. All are perishable plant material. Such discards do not create an environment of opportunity in the same way. When chimpanzees use stone tools, they abandon the tools that have been used—hammers and anvils—and may reuse them on another occasion, probably for the same function (Boesch and Boesch 1984), or they are tools that can no longer be used—broken hammers—that may give the appearance of being stone artifacts when excavated by archaeologists (Mercader, Panger, and Boesch 2003). The exaptive opportunity provided by the stone debris left by hominins is an accidental outcome of three features of hominin tool making that distinguish it from chimpanzee tool making:

1. The relevant hominin tool-making activities used raw material that is stone and thus endures for millions of years.
2. The product that was used resembles the product that was abandoned so that abandoned flakes may prove useful on another occasion. Hominins could have returned to the previous knapping location for tools, just as chimpanzees recover previously abandoned hammers.
3. The hammer and core may be reused to produce more flakes, in effect recognizing that the previously abandoned knapping floor is a "new" source of stone raw material.

We then turned the question around and asked whether the hominin evidence would withstand the sort of scrutiny that had been applied when assessing whether the chimpanzee evidence should be called cultural. For this exercise we applied some criteria developed by McGrew and Tutin to assess the significance of the grooming handclasp they had observed at Mahale but not at Gombe (McGrew and Tutin 1978). In doing this, they took criteria they had derived from Kroeber and Kluckhohn (1963) and assessed whether the handclasp showed innovation, dissemination, standardization, durability, diffusion, tradition, and non-subsistence behavior or was naturally adaptive. The authors expressed some doubt whether the grooming handclasp met all of these criteria, particularly in the absence of longitudinal studies that might show innovation and of studies showing dissemination of the behavior among peers or diffusion among groups. McGrew and I showed that, contrary to expectation, the evidence of early stone tool making might *not* be sufficient to claim that the behavior of early hominins was cultural by these criteria. In particular, it is also relatively difficult to make the case for innovation, dissemination, or diffusion. McGrew and Tutin left the possibility that the chimpanzees had not quite demonstrated all of the requirements to be called cultural, although McGrew has since strengthened his position (McGrew 2004). We left unexamined the question of whether our conclusion about the earliest stone tools demonstrates the poverty of the analytical method or the inflated assessment of the usual interpretation of the significance of the earliest stone tools.

Whatever the resolution of that opposition, no one doubts that stone tools became part of the distinctively cultural behavior of subsequent hominins and humans. We now have analyzed the earliest stone tool making into small behavioral elements that show differences between hominins and chimpanzees—but not those we expected—and we can consider these as elements of behavior relevant to building a picture of the different components that have contributed to changing cognition. What is important here is not that stone tool making marks a fundamental cognitive change but that it was part of an emerging process of cognitive evolution.

"SEMANTIC" ROLES AND STONE TOOLS

In these examples, there is a repetitive structure to the relations among the animals (both chimpanzees and early hominins), the objects, and the actions they carry out. Using the approach to language of Fillmore (1968), we might say that these repetitive structures have their own semantic meaning—although we should be cautious about labeling as "semantic" aspects of the behavior of animals that are not language using. The Budapest research group, inspired on this occasion by Phil Barnard, showed that many of the roles we routinely call semantic among people could also be found among chimpanzees (Byrne et al. 2004). This might seem a trivial observation, since it has a superficial similarity with the ascription of roles and motivations to other animals through the phenomenon of anthropomorphizing, especially in children's stories. Anthropomorphizing, however, typically attributes human characteristics to nonhumans that do not normally have those characteristics; the process we are describing here is one in which we are giving names to characteristics that nonhumans do have. But there is a more important point here, particularly as it relates to stone tool making.

These repetitive structures can also be found among the early hominins using stone tools (Table 9.2). But the difference between these cases and those identified for chimpanzees is that six of these eight examples leave a distinctive material product. The two exceptions are the dative role and the experiencer role: we cannot directly infer from the stone debris alone either material exchange or the emotions involved, although participants in the gift and in the

Table 9.2. Examples of the repetitive structures associated with stone tool making and use that may become roles that have semantic meaning. Arguably, those roles that are shaded all leave distinctive, enduring products when they apply to relationships among the hominin, Lucy, and stone tools.

Agent	Lucy fetched the stone
Counteragent	Lucy hit the stone with a rock
Object	The stone breaks
Result	Lucy made a flake
Instrument	The flake cut the carcase
Dative	I gave the meat to Lucy
Experiencer	Lucy felt good about having made a flake
Locative	Lucy walked away from the flake scatter

emotion of tool use may have their memories prompted by the sight of the tool. Repetition of the actions with similar material products provides the circumstances for the hominins themselves to identify regular patterns among these actions and products. In this way the repetitive structures might become more than just regularities of behavior; they might begin to be conceptualized semantically. This process, I suggest, is exactly the same as what archaeologists do in giving meaning to such archaeological records.

These are the circumstances for changes in the cognitive system of the hominins through the modification of their behavior by the creation and recognition of the patterns of their own behavior and of their own particular microenvironments. The process is significant.

1. A new behavior leads to the production of distinctive and enduring material products.
2. The persistence of these products provides the opportunity for reflection on the relationships between the past process of production and the roles played in their production.
3. Generalization from such reflections leads to the recognition of the semantic nature of those roles.

COGNITION AND STONE TOOLS THROUGH PSYCHOLOGICAL AND LINGUISTIC THEORY

This analytical process of building up a picture of the different components that have contributed to changing cognition was pioneered, among archaeologists, by Tom Wynn (2002). In his early works, he used the framework of ontogenetic cognitive development devised by Piaget to show some of the simple cognitive changes that have occurred through the changing sequence of stone tool industries (Wynn 1979, 1981). Whatever Wynn or others now think of these early attempts, they did highlight some aspects of stone tool knapping that are still important in assessing cognitive evolution through the analysis of stone tools.

Thus, Wynn assessed the Oldowan as requiring simple spatial concepts such as proximity and order typical of the childhood stage of preoperational intelligence. Wynn concluded that it was not until late in the Upper Paleolithic that stone tools themselves carried a semiotic load—particularly that they may have functioned symbolically (Wynn 1999). The important point is that Wynn's insights derived from the use of apparently well-established theory from another discipline and the identification of the observations that would be relevant to allow interpretation of the material record in light of that theory.

In keeping with the present analysis, I suggest that proximity and order are examples of the small behavioral elements that made a cognitive difference. Following from this, the repeated requirement to use these concepts, however unreflectively, provided the environment of opportunity for mental awareness of them, and hence of their application to other domains. In this view, Oldowan hominins should not be interpreted as having reached the childhood cognitive state of preoperational intelligence; rather, through their actions and the selective reflection on them, Oldowan hominins created that cognitive awareness that Piaget called preoperational intelligence. As so often in the interpretation of stone tools, the outcome may appear similar, but the cognitive process that led to it may well have been organized differently.

Arguably, the action sequence involved in the repetitive selection, clipping, folding, and consumption of stinging leaves by gorillas has some of the same procedural properties, particularly of proximity and order, but these only ever occur within this action sequence. In stone knapping, each application of the concepts of proximity and order required unique judgments about the individual core and hammerstone, and the outcomes are still visible on the resulting product. The combination of the elements of the action sequence must be assessed for each knapping episode. But in gorilla leaf preparation, the clipping and folding occur as in a single action without any possibility of changing the order of events—the sequence is applied without thought—and in the absence of a material product, there was no opportunity to turn the roles exhibited by those actions into an awareness of the semantic nature of the separate actions (clipping, folding, etc). In this view, the evolution of the reflective aspect of cognition was a consequence of making stone tools, not a prerequisite. It is arguable that apes have a spatial-praxic cognitive subsystem that coordinates the relationship between visual inputs and the behaviors exhibited through the limbs or related vocalizations (Barnard et al. 2007), but, I argue, the persistence of stone tools permitted cognitive awareness at another level, through the capacity to separate the component actions of the process of knapping.

In another attempt to look at the cognitive significance of stone tools, I (Davidson 2006) used a theoretical argument by the linguist Ray Jackendoff (1999, 2002) in which he described what we might call the comparative anatomy of language. In this, Jackendoff identified aspects of language that might be regarded as fossils of earlier stages of language-like communication with the intent to find traces of past human communication in "language as we see it today" (Jackendoff 2002:233). He attempted to break the language capacity into quasi-independent parts, for without this identification of separate and varying modules, it is difficult to see that selection can operate on an evolving language capacity. Having done this, he was then concerned with showing how the rules of combination of those separate parts also could have emerged through evolutionary processes. Botha (2003:8) has also recognized the importance of identifying the "(pre)linguistic entities that are believed to have undergone evolution" and acknowledges the importance of Jackendoff's attempt to find these in such "quasi-independent parts."

Language Phase 1: The Expletive Stage

In Jackendoff's argument (2002:239–241), the most primitive fossil of early language evolution would be the use of exclamatory words of high emotion, such as any of those expletives we might expect to be uttered when a hammerstone hits a thumb instead of a core, and a whole range of similar words used in similar or unrelated contexts. Yet dogs, and doubtless other animals, utter cries of pain when kicked (I am told), but they do not, as people do, change those vocalizations depending on the language of their caregivers. Our conventional expletives are generally language-specific (e.g., the French say *merde*, but English-speakers do not; and indeed the force of the expletive in this parenthesis is diminished by being uttered in a foreign language) so there is already a degree of semanticization that separates this type of utterance from expressions of emotion by other animals.

Closely following this, according to Jackendoff, would be the one-word stage of child language acquisition. Unlike the widely discussed vervet calls (Cheney and Seyfarth 1990), these single-word utterances are genuinely symbolic (semanticized in just the same way as the expletives) and learned—that is, some children learn to say "eagle" and others "*aguila*," arbitrary utterances but conventional in the language of their parents—but generally lacking syntax. Noble and I (1996) presented a detailed case that symbols were the fundamental invention in the evolutionary emergence of language, and unreflective learning was the way in which they were passed on between generations.

Language Phase 2: The Symbol Stage

Following on from this, in Jackendoff's scheme, is a requirement that the symbols that feature in the more primitive phase be part of an open class of symbols. Arguably this is a property of the utterances being genuinely symbolic, both arbitrarily related to their referent as well as conventional within a group of communicators. This property of symbols allows almost infinite expansion of the vocabulary, although there are further cognitive requirements particularly about learning and memory capacity.

Language Phase 3: The Symbol Construction Stage

For Jackendoff (2002:242–245) a key aspect of increasing the number of symbols in such an open system was the emergence of a phonological system separated from meaning, allowing the utterances to be made up of combinations of meaningless modules. A similar productivity followed from the invention of the alphabet, rather than logograms, as a means of representing speech in writing (Skoyles 1990).

Language Phase 4: The Phrase Stage

The final stage of Jackendoff's identification of primitive features is the appearance of rules of word combination, because this is crucial to the emergence of language as we know it. The reasons for this are straightforward: without rules of combinations of the modules from which language is composed, vocabulary can increase through the mechanisms of Phase 3 but vocabulary size is limited by the capacity of brains to store the information and, as Jackendoff (2002:246) showed, there are further limitations because word combinations without syntax would rapidly become incomprehensible.

Building on this four-phase scheme, I speculated about the sorts of archaeological signatures that might correspond with these stages (Davidson 2006). There is still a rather non-specific underlying assumption that the language and technical abilities might both depend on a common generalized cognitive ability—an assumption that has some support from Greenfield's (1991) experiments with "grammars of action" (see Moore, Chapter 2).

My previous speculation fleshed out the four-phase scheme with specific examples, using the standard interpretation of progressive changes in stone tool

Table 9.3. Possible equation of "comparative anatomy" of linguistic "fossils," as defined by Jackendoff (1999, 2002), with events in the archaeology of stone tools.

Jackendoff fossils (Jackendoff 1999, 2002)	*Archaeology (Davidson 2006)*	*Evidence/date*
Exclamatory words of high emotion	Limited instinctive use of (unmodified?) materials	Prehominin tool use, cf. chimpanzees (Whiten et al. 1999)
Open class of symbols	Added variety in tools	Flaked stone tools by 2 myr (Wynn and McGrew 1989)
Discrete meaningless modules	Combined actions before tool achieved	Acheulean handaxe (Davidson 2002)
Rules about combinations of modules	Set patterns to combinations of actions	Levallois technique (Boëda 1988; Foley and Lahr 1997)
Word order	"A tool to make a tool"	Indirect percussion (Bar-Yosef and Kuhn 1999; Davidson 2003b)
Modifying words modify the word next to them	Tools with specific sequences of use	Bone tools (Henshilwood, d'Errico et al. 2001; Henshilwood, Sealy, et al. 2001)
Compound nouns	Multiple component	Hafting (Boëda et al. 1999)

technology (Table 9.3). I have indicated elsewhere (Davidson 2002, 2003a) that I am not convinced of the reality of this sequence, but it was a first approximation. What follows is a slightly more detailed and critical consideration with variations on the previous speculations more in line with my skepticism about the standard sequence.

Tools Phase 1

The equivalent in tool making of the expletive or one-word phase of language, perhaps, is represented by chimpanzee tool making for termiting. In a context of the presence of termite mounds, chimpanzees obtain grass stems, strip extraneous leaves from them, and use them as tools to extract the termites. No great cultural knowledge appears to be necessary for this action and in this respect it lacks equivalents of the semanticization of expletives seen (or heard) in language. It may be that we should compare the "expletive" stage with the earliest stages of stone tool making—the removal of flakes from cobbles, albeit in sequence (Delagnes and Roche 2005). This would be consistent with the analysis of Davidson and McGrew (2005) that early hominin stone use did not meet all nominated criteria to be considered cultural. Wynn and McGrew (1989) argued that Oldowan abilities had several similarities with those of apes. It is a matter of judgment whether the earliest knapping involved symbolic representation in the way the one-word stage does for very young children, or for anguished knappers. In the knapping at Lokalalei 2C (Delagnes and Roche 2005), "the flakes are the intended end products and the cores clearly fall into the category of technological waste, even though some bear the signs of retouch suggesting a secondary use as tools." It is difficult to understand how the archaeological conclusion is reached that cores are waste when the knappers themselves (or other hominins finding the knapped products) seem to have formed the judgment that these were suitable for retouching and use as tools. But this is a precise analogy for Jackendoff's one-word phase where the individual utterance, almost involuntary, can come to be part of communication at another level.

There is a further slight analogy with the nature of symbols in the distancing of the tool selection from the raw material acquisition and the sequence of flake removals. This is not quite an example in which the flake chosen for use "stands for" something other than the other products of raw material selection and flake production, but insofar as other flakes might have performed similar functions, the stone artifact production is distinct from the preparation of a termiting wand. In that case, the wand emerges by stripping leaves from the useful stem, but the leaves are trimmed precisely because they are not useful in any circumstances. I suggest, therefore, that the analogy with Jackendoff's expletive stage could work for stone tool making as it does not for the preparation of a chimpanzee termite wand: the cognitive process required to make stone tools provides the basis for more productive use of stone without the specific mechanism. But the cognitive demands of this earliest knapping do not go much further for, despite the appearance of organization in the knapping, the knappers "had the cognitive abilities to exploit angles when encountered but not to create new ones" (Delagnes and Roche 2005).

Tools Phase 2

How and when this process became equivalent to Jackendoff's "Language Phase 2" by turning into an "open class of symbols" or equivalent knapping gestures is correspondingly less clear than I previously suggested (Davidson 2006). It may be that the creation of new angles on platforms is one of the keys to this stage. If it were true that artifacts such as the Acheulian biface or handaxe were the intended products of a long sequence of knapping, all of which was otherwise unrelated to tool production, then I would suggest that it has some of the hallmarks we might expect. Insofar as production of the finished artifact required an ability to create and maintain the acute angles of the margins of the handaxe, this stage does represent a significant change from the earlier stage. But the value of this argument depends on the widely held assumption that the handaxe was an intended final product rather than a frequent outcome of knapping in which acute angles happened to be maintained during the efficient production of flakes for use.

But I have argued previously that many of the assumptions about this degree of intentionality are false (Davidson 2002; and see Byrne 2005:167) and others have agreed (Clark and Riel-Salvatore 2006): the appearance of uniformity of dimensions and shape of handaxes has much to do with the methods of classification by archaeologists (Dibble 1989); raw material and reduction intensity have a stronger bearing on the form of the objects than expected if they conformed to a mental template (McPherron 2000); conjoins show that what was carried from the site after initial preparation was not simply identifiable as a handaxe (Bradley and Sampson 1978) but could be considered a bifacial core; flakes from handaxes are sometimes missing from conjoin sets (Bradley and Sampson 1978) and some were used (Potts 1989: 481); some handaxe forms said to be the aim of knapping occur in the middle of reduction sequences in replication experiments (Bradley and Sampson 1986); and flaking of cores continued after the handaxe form was reached (Davidson 2002). Analyzing a database of artifacts (Marshall et al. 2002) highly selected to conform to the stereotype of handaxe form, including symmetry, others have shown that symmetry, one of the fundamental definitions of handaxes, is not the dominant form (McNabb, Binyon, and Hazelwood 2004). It seems likely that even more uncertainty would be introduced by considering the whole range of cores in an assemblage (one rare example of a study that includes both handaxes and the other cores is the analysis of Olorgesaile by Isaac 1977) rather than singling out the handaxes for special attention.

In practice, the openness of the class is a hallmark of the phenomenon Mellars (1989) called "imposed form," where the productive potential of raw material modification is harnessed to create an artifact in which the form of the final product is relatively independent of the constraints imposed by the mechanics of the application of forces to raw materials (Davidson 2003a). This ability seems to be more closely related to Phase 3.

Tools Phase 3

Jackendoff's identification of a phonology of meaningless modules as crucial to the proliferation of symbols is equally enigmatic when we seek analogy in stone artifact technology, but there is a case that it is relatively late in appearance.

Holloway (1969) previously argued that the opposition between (core) tools and waste products could be likened to the contrast between words and phonemes, but we have countered this (Noble and Davidson 1996:168) on the grounds that the earliest flakes were used (Keeley and Toth 1981) and there is uncertainty about what was the finished artifact (Davidson 2002).

In principle, the standard story about the Levallois technique—prolonged preparation of cores by "anticipatory flaking" to permit the removal of long-foreseen "objective" flake or flakes (Boëda 1988)—would meet the requirements of this phase, in that the anticipatory flakes appear to have no "meaning" as potential tools. This is the technology that Foley and Lahr (1997) refer to as Mode 3. But as I have argued previously, substantial evidence suggests that the standard story is not plausible (Davidson 2003a; Davidson and Noble 1993; Noble and Davidson 1996:200–201): there are assemblages in which the "final flake" is preserved beside the core (Pelegrin 2005; Schafer 1990); there are examples of conjoined cores in which the supposedly anticipatory flakes were removed, presumably for use (Van Peer 1992); the evidence from use-wear shows that non-Levallois flakes were more often used than Levallois flakes (Beyries 1987).

In addition, de la Torre and colleagues (2003) have shown that some Oldowan assemblages from Peninj contain cores that have much in common with the pattern of reduction used in the Levallois technique, but without the removal of the "final" flake. A similar judgment was reached by others about the possibility of Mousterian cores in early assemblages at Olduvai (Davidson and Noble 1993; Gowlett 1986). I am not suggesting that the Levallois technique occurred in such sites, rather that there is no reason why the primary pattern of flaking should be regarded as significantly different in the two cases. In the Peninj case (de la Torre et al. 2003), where the prepared cores do not have the "final" flake removed, we are dealing with core reduction for the production of flakes. When it is part of the Levallois technique, we are dealing with core reduction as preparation for the removal of the final flake or flakes. Yet the core reduction in both cases is fundamentally similar—bifacial flaking from a core with masses distributed asymmetrically about the plane.

Is there a more plausible candidate for such combination of "meaningless" knapping leading to the production of something considered meaningful only through the combination of such gestures? It might be seen in the technique used in the European Upper Paleolithic by which a core is prepared for the production of a large series of elongated flakes known as "blades." In this technique, flakes are removed in two series but in opposite directions to produce a ridge formed by the intersections of the flake scars. The mass along the ridge allows the core to be rotated through 90 degrees so that a long flake or crested blade (the *lame à crête*) can be struck whose margins form the ridges for the removal of subsequent elongated flakes (Tixier, Inizan, and Roche 1980:82–83). Such preparation is present but rare (less than 3 percent of the assemblage) in the early Howiesons Poort layers at Rose Cottage Cave in South Africa (Soriano, Villa, and Wadley 2007). The outcome of this knapping is that a core is set up where the successive products are unlike the crest that is essential to the process. Crested blades are also present in blade-producing Levallois industries in France, although Delagnes and Meignan (2006) point to several differences between Middle and Upper Paleolithic blade production.

There is a further point to be made about the production of blades by the preparation of cores using crested blades. The reduction sequence involves a module of knapping routine that generates both flakes and the crest in which both products are unlike the blades removed from the core. Many blades can be struck from the core once it has been set up in this way. The combination of apparently unrelated modules of this type is what indicates complex cognition, not the presence of blades. Blades occur in many assemblages in low percentages (Davidson 2003b), and Moore has shown that they are inevitable in some knapping where the reduction sequence is not organized around their production (Moore 2007). It is likely some blades occur as accidental by-products of reduction sequences that generate other tools and sometimes because particularly elongated raw materials permit their production. It may be that some of the examples of unexpectedly early blades are accidental products that occur in small percentages in their assemblages or which arise from a particular initial form of the raw material (e.g., McBrearty and Brooks 2000). At Rose Cottage, such knapping initiation using natural cortical ridges is much more common (12 to 14 percent of the assemblage) than the use of crested blades (Soriano, Villa, and Wadley 2007).

Tools Phase 4: Hafting; Rules about Combinations

Jackendoff's fourth phase—rules about combinations—has a direct parallel in the production of stone and bone tools, which necessarily were composite. The construction of a watercraft to get to Australia by at least 45,000 years ago (O'Connell and Allen 2004) is a prime example (Davidson and Noble 1992). Notwithstanding earlier skepticism (Holdaway 1989), incontrovertible earlier evidence has now accumulated that stone artifacts were part of composite technology. There are two lines of evidence. The first is based on the artifacts themselves, for example, the discovery of a stone tool embedded in the bone of an animal at the Syrian site of Umm el Tlel that is at least 50,000 years old (dated by thermoluminescence) (Boëda et al. 1999). The analysis of attributes of points as projectile tips suggests that projectiles launched with a bow or spear-thrower postdate 50,000 years ago, although hafting of stone tips to spears, possibly used for thrusting rather than throwing, may be earlier (Shea 2006).

The second line of evidence is the discovery of hafting materials. Interpretation of hafting materials is more difficult because in both early instances there is no evidence that the artifacts were attached to another object. The first case, from Italy, probably older than OIS6, or more than 130,000 years ago (Mazza et al. 2006), has the appearance of Australian handheld knives, where the resin forms a haft protecting the hand (Roth 1984 [1897]: 151). The second case is the lumps of processed resin from Königsaue dated to just after 50,000 years ago that are said to have required processing to separate the pitch from the birch bark (Koller, Baumer, and Mania 2001).

Such recent discoveries lend credence to claims by Callow (1986b:307–308) that several Mousterian points and elongated Mousterian points at La Cote de St. Brelade, Jersey, United Kingdom, had flaking of the tips, which could be interpreted as resulting from impact damage during use as weapon heads. These were found in layers 5 and A, probably dating to the beginning of OIS6, perhaps 200,000 years ago (Callow 1986a:78–79).

If we accept, for the sake of argument, that such evidence of composite technology really is analogous to the "Phrase Structure" phase of Jackendoff's scheme, then we might be led to argue that this technology is evidence of language having emerged in Europe at these times. All of these examples are earlier than the generally accepted ages for the appearance of modern humans in Europe, and indeed, the specimens from La Cote de St. Brelade predate the claimed earliest appearance of modern humans on anatomical (Clark et al. 2003; Trinkaus 2005), genetic (Forster 2004), or behavioral (Henshilwood and Marean 2003) evidence. On the face of it, this seems to suggest that the most distinctive aspect of modern human behavior emerged in more than one species of hominin in more than one region (d'Errico 2003; Zilhão 2006). How we resolve this paradox within our current ways of thinking is one of the big challenges for the future.

CONCLUSION

For much of prehistory, the evidence of the making, use, and abandonment of stone tools is not only the most abundant but also the best evidence for the evolution of human behavior. I have tried to show some of the steps that might be needed to tease out inferences about cognition from stone tools. We need clear theoretical guidance about what to look for, but we know that we know much more than nineteenth-century European scholars did about stone flaking (e.g., Dibble and Pelcin 1995), about the empirical record in Europe (e.g., Cabrera Valdés et al. 2006; Conard and Bolus 2003), and vastly more about the rest of the world (e.g., McBrearty and Brooks 2000).

Stone tools, particularly through the studies by the authors in this volume, may well be the best way to get at the really important changes in the evolution of our ancestors, but we need to proceed cautiously and rigorously and not be seduced by interpretations of partial evidence simply to confirm our prejudices about interpretation within our comfort zones. The record of stone tools is consistent with the new uncertainty that attends the interpretation of hominin cognitive evolution as a result of new discoveries in Africa and Europe. Some of our earlier attempts to interpret the broad patterns of evolution depended on the very limited nature of the existing archaeological record.

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TEN

Current Developments in Inferring Cognitive Capabilities from the Archaeological Traces Left by Stone Tools

Caught between a Rock and a Hard Inference

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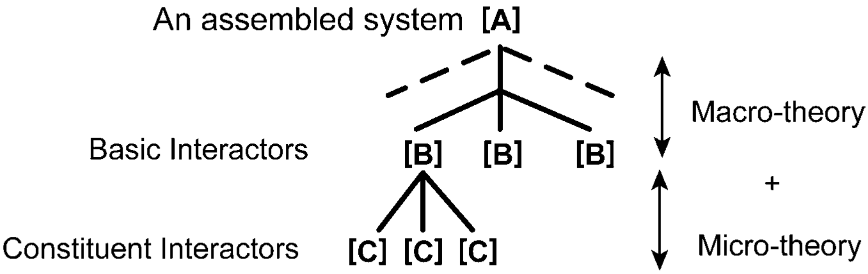
When observing or touching a stone tool made many hundreds of thousands of years ago, it is hard to imagine anyone not experiencing at least some intellectual curiosity, wonderment, and perhaps even other emotions about the nature of the minds and lives of the species that made it. For non-experts in archaeology, such as myself, dangers abound from that point forward since many of the key arguments have already been well rehearsed by the experts with their deep knowledge of lithics and the accompanying evidence of forms, be they imposed or otherwise; their distributional properties over time; and the strategies that could have given rise to them and their likely uses. For a behavioral scientist used to making inferences only from the effects of variables that are under experimental control and that give rise to distributions of, for example, categories of observable behaviors, reaction times, or errors, I find myself having to work into and reevaluate the very processes of inference that allow us to link evidence concerning stone tools to the possible properties of the minds that created and used them. Not only are we unsure of the number of distinct hominin species, as the recent discovery in Flores reminds us (Brown et al. 2004), but also the evidence that is available is incredibly sparse and is spread over diverse sources such as



10.1. A constrained system of basic entities that interact (modified from Barnard et al. 2000).

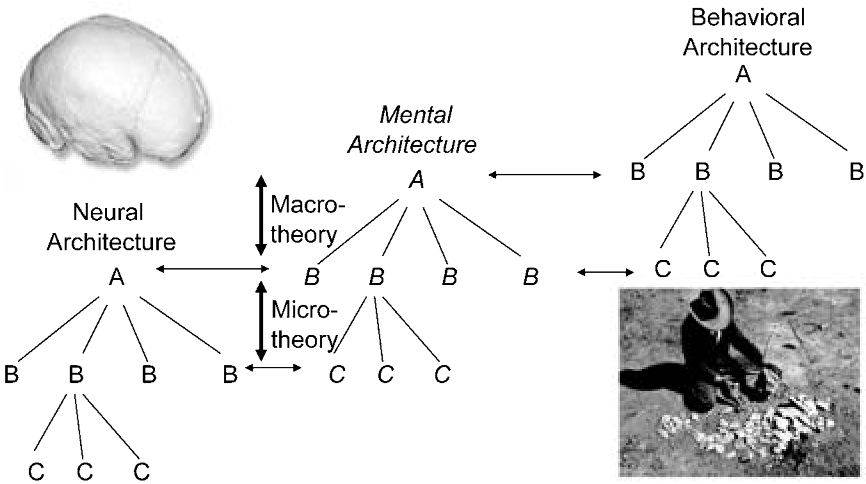
bones, artifacts, footprints, or habitats. Yet, latent within those inherently static traces is evidence about dynamics. Particular categories of behaviors are implied by the form and variation in preserved artifacts, whereas key dynamics of behavior over time are indexed by the sequences with which flakes were removed. The plausibility of those dynamics can even be explored by modern minds testing out alternative means by which such artifacts could have been created.

Although this is all meat and drink to those well-versed in archaeological reconstruction and argumentation, I feel caught very much between a rock and a set of hard inferences. I am most certainly not qualified to raise and comment on detailed archaeological points, and so I will focus here on positioning the individual contributions within a framework for thinking about the behavior of systems in general and the issues associated with inferring properties of mental systems from traces in physical ones.

Several qualitatively distinct types of systems are addressed in archaeological enquiry as means to the end of making inferences about the minds of hominins—notably, these include neural systems, behavioral systems, and ecological systems. Although qualitatively distinct, all such systems can be thought of as made up of "interactors," a term originating in computer science (Duke and Harrison 1993). These are entities that interact under different sorts of constraints to produce behavior, be that behavior a pattern of neural activity, a sequence of thoughts, or overt actions that result in the creation of a tool. In order to make a simple point, Figure 10.1 shows a small hierarchy in which a number of basic interactors (*B*s) make up a system, or an assembly in focus (*A*), whose behavior might be of interest to us. In the case of a simple system whose behavior is denominated in units of action, we might have one system "in focus" for knapping where the relevant *B*s are an agent hominin, a core, a hammer, and some flakes, whereas for a tool-using system we might substitute the core and hammer with a carcass and parcels of meat. Of course, just knowing that the system was composed of a number of physical entities tells us very little. In the context of analyzing today's technologies, we have argued that the behavior of any system of interactors can be thought of as determined by four quite simple and generic constraints relating to the way the interactors are configured, the capabilities of individual interactors to change states (be they physical or information states), the requirements that must be met for the capability to be exercised, and the way in which the entire system is dynamically controlled and coordinated over time (Barnard et al. 2000). Together these provide constraints that determine a particular trajectory for behavior, and a theory would need to specify the principles that govern the generation of a range of behaviors. Barnard and colleagues (2000) also provide examples of how these four classes of constraints can be linked together via principled relationships. They summarize the components of macrotheory in the following way where *Fn* stands for "function of":

> Trajectory of System behavior: Fn (Configuration, Capability, Requirements that need to be met; Dynamic control and coordination over time).

Although rather abstract, the important point is that this function can be applied to the behavior of any system. The terminology maps relatively naturally onto how one might talk about military operations and logistics. A tank may well have the capability to fire shells over a range of distances but cannot do that unless obvious requirements are met in terms of the availability of an appropriately trained crew, fuel, and ammunition. In the case of a stone toolmaking system, for example, the "system" will typically have a spatial configuration that dynamically changes over time, in this case under the direct control and coordination of an agent who must meet the requirement of having appropriate mental capabilities and practice. Likewise, the hammer and core must meet particular requirements in terms of their physical properties of shape and hardness to create a tool that is fit for purpose. To have a macrotheory of that system's behavior we need to specify each of the components, their configuration, their capabilities, the requirements that need to be met, and how the behavior of the system is controlled and coordinated to a useful degree of approximation. A macrotheory of the system is, in and of itself, just an approximation. To fully model a system's behavior also requires us to consider how properties of the individual entities that it encompasses work together; for example, the capabilities of a multicomponent tool involving hafting require us to understand how the constituents of the tool themselves are put together. The same obviously applies to the mental capabilities of tool makers in terms of their knowledge of materials, their spatial-praxic skills, and so on. This is represented in Figure 10.1 by allowing for a basic interactor (*B*) to be decomposed into its constituents (*C*),



10.2. Three layered systems of interactors (picture on right, Alyawara man knapping using a steel hammer, courtesy of Lewis Binford).

and an account of the basic interactor would form a microtheory of a particular system component. There are both top-down and bottom-up constraints on what a *B* can do. On this scheme, a complete "theory" of a tool-making system would involve having both a macrotheory of that system's behavior and a collection of micro-theories of each of its components.

Of course, the actual evidence covered in this book does not just relate to a tool-making or tool-using system; it seeks to interrelate the physical evidence in the record with both the mental architecture of the hominins that left the evidence as well as their neural systems. Figure 10.2 therefore expands the basic form of Figure 10.1 to provide a framework involving three levels of systems, topicalized on neural architecture, mental architecture, and behavioral architecture. The basic interactors in mental architecture can be thought of as composed of processes that, for example, handle visual, auditory, and bodily states as well as the memory representations that they use to support action selection and execution. A macrotheory of mental architecture would, in principle, tell us how all the components worked together to determine thought and behavior, whereas the associated collection of micro-theories would specify how attention, memory, or language skills actually work in detail. The behavior of a mental architecture is denominated not in actions but in the processing of information. In the case of the neural systems in the brain and its peripheral inputs and outputs, the "basic interactors" are large-scale circuits and their behavior is denominated in terms of electrical impulses and neurotransmitter release.

A number of points arise directly from this multilayer diagram. First, the key theme of this particular selection of articles concerns the cognitive significance of particular patterns in the use of stone tools and their implications for the evolution of cognition. To this end, the mental architecture of extinct species is our primary focus of attention and here the number of levels is restricted to three. Additional system levels are, of course, relevant and it would be a relatively straightforward matter to extend the overall scheme on the right-hand side to larger scale social interactions and ecological systems or on the left-hand side to whole bodily systems or to even cellular-level systems including genetics. Second, a macrotheory of neural architecture should inform us about what underlies the basic things that interact in the mind and their capabilities, whereas a macrotheory of mental architecture should inform us about the capabilities that are enabled within a behavioral system. We require coherent mappings from one system level to another—represented here by the horizontal arrows between system levels. The horizontal double-headed arrows in this diagram relate system levels in a manner not unlike the classic distinctions offered by Marr (1982) between computational, algorithmic, and implementational levels of explanation. However, the form adopted here allows us to consider decompositions of interactors of all types, be they physical systems, information-processing systems, or biological ones.

The diagram also implies that we cannot directly move from a neural theory to a behavioral one without drawing on theories of mental architecture. It reminds us that what is required for strong claims to be made about the relationship among brain networks, minds, and behaviors actually rests on a rather complex web of interdependencies. So, for example, a property of our whole brain, such as its size, or the relative size of its constituent lobes tells us little about the behaviors it supports without a wide range of assumptions being made about the units of which it is composed as well as what goes on in mental and behavioral architectures. Note that the whole brain may be made up of many complex networks, each one being an assembly (*A*) of networks (*B*s) that themselves can be deconstructed (*C*s). When we map from a neural level of explanation to a psychological one, we typically discard the fine-grain detail (the nature of the *C*s) and account for mental processing only in terms of a macrotheory of network operation (*A* and *B*s). The same could be said about any other chain of inference across the diagram. The horizontal arrows in this diagram imply that a macrotheory of mental architecture is required to understand what kind of capability can be invoked in a behavioral system involving the animate agent within that architecture. There is no horizontal arrow from isolated constituents of mental architecture to behavioral architecture since the behavior of a mind is seen as a product of all its components acting together. This implies that inferences about specific constituents of mental architecture to behavioral architecture are, in principle, unsafe.

Third, the evidence we have to date from the archaeological record about what might constrain behavior at each level of system in extinct species is well-known to be incredibly sparse and incomplete. It goes without saying that we cannot do behavioral experiments on species that no longer exist. Nonetheless, we are able to draw on comparative evidence from the behavior of modern human brains, minds, and tool making as well as that from other species that share a common ancestor. In this context, it is important to note that, although we have a great deal of data about modern human brains, minds, and tool-making behaviors, there is far less agreement about the theories that might best account for those behaviors. Current psychology and cognitive science, for example, has a vast body of empirical findings covering all domains of our mental life. Our theory base is, however, most richly developed for micro-theories of specific aspects of mental life, such as language comprehension/production, visual and auditory perception, attention, short- and long-term memory, and thinking and decision making. Although there have been successive attempts to develop unified theories of cognition (e.g., Anderson 2005; Newell 1990) or macro-theoretical accounts of relationships between cognition and emotion (e.g., Teasdale and Barnard 1993), there is little overall consensus at either micro- or macro-theoretical levels (for sample coverage and controversies see Eysenck and Keene 2005; Stainton 2006). In addition, well-formed theories in psychology seldom endure for more than a couple of decades at best. For the archaeologist seeking to map properties of stone tools to properties of the evolution of cognition there is a rich seam of alternative theories available. Since mainstream ideas about mental architecture, be they framed at a macro-theoretic or micro-theoretic level, mostly lack an evolutionary dimension, a key aspect of how to map them to the archaeological record is left open, and there can be little certainty that those chosen are actually valid for modern minds, let alone the minds of extinct hominins, or that the theoretical constructs they employ will endure sufficiently far into the future in the empirical context of archaeology where the accumulating pattern of evidence from bones and stones may change.

What Figure 10.2 illustrates is the nature, scale, and scope of the inferential issues and challenges that need to be addressed when seeking to relate the properties of stone artifacts to the minds and brains of the tool makers and tool users. At this point, one extreme and natural reaction of a typical laboratory behavioral scientist might be to observe that the whole enterprise is basically intractable. Another reaction would be to observe that we should only expect very small steps to be made in filling out the many unknowns. The important thing is to develop more refined hypotheses that will be open to test in a context where the crucial evidence may only emerge on a far longer time scale than that of laboratory research in behavioral science. If we take Figure 10.2 as a target rather than as a full-fledged reality, then the collection of chapters in this volume and numerous other reports in the current literature present us with evidence from precise methods of archaeological investigation that establish key features of configurations, capabilities, requirements, and the dynamic control and coordination in behavioral systems that make and use tools.

The form of stone tools has been used to infer different levels or types of mental competence. For example, Holloway (1969) argued for homologous relationships between stone flaking and language with a grammar and semantics of stoneworking, and Wynn (1979) argued that spatial operations, discernible on Acheulian handaxes, are indicative of fully operational thought, as defined within a Piagetian framework, whereas pre-Acheulian tools required only pre-operational intelligence. These approaches are making what amounts to diagonal connections, not present in Figure 10.2, directly from specific properties of "tool" interactors in a behavioral system to an attribute of one or more basic interactors in the mental architecture of its maker without taking into account a full macrotheory. Since there are powerful reasons to question assumptions requiring a direct link between an isolated property of artifact form and the psychological intent of its maker (e.g., Davidson 2002), we naturally need to proceed with caution. Moore (Chapter 2) offers an intriguing and conservative approach. He elegantly analyzes the design spaces underlying several different types of tool, taking into account both motor action and ideational aspects of those design spaces. The key units include basic flake units, bipolar flake units, and complex and elaborated flake units, as well as their combinations in the serial removal of flakes in a reduction sequence. In this analysis he carefully represents early knapping as the serial combination of basic flake units with a simple algorithm applied in long chains. Later developments involved the addition of a second hierarchical tier to produce a complex flake unit requiring recognition that the platform could be modified by anticipatory flaking on the obverse core face. He argues that complex flake units were in place during the Middle Pleistocene and elaborated flake units by the Late Pleistocene with the possibility that both forms were being used to produce Acheulian handaxes. Subsequent developments, culminating in the complex process seen in the Neolithic, involved the development of increasingly complex hierarchical combinations of flake units.

I would like to make two simple points about Moore's design-space analysis. First, it focuses cleanly on how agents generate form by knapping. Although the design-space analysis has its own terminology, it has close connections to what Figure 10.2 requires for a macrotheory of behavioral architecture as applied to knapping. The essential capability that changes the state of the core involves Moore's rotate-turn-tilt actions and a percussive and precisely aimed blow of some force with a hammer (Byrne 2004), the result of which is the separation of a flake unit from the core. In order for a flake with particular properties to be detached, certain requirements need to be met in terms of the geometry of the core, its orientation, the angle at which the blow is applied, and the hardness of the implement used to apply the blow. Aspects of each are identified in Moore's analysis. Most crucially, attributes of the control and coordination of the whole behavior trajectory can be captured in terms of tree-structure diagrams specifying attributes such as the length of chaining or where multiple objects form subassemblies in a hierarchy—in Moore's terminology, the "architecture of the reduction sequence." This represents an important step in theory formation and one that is prudent in what it has to say about any plausible horizontal linkages between mental architecture and behavioral architecture in Figure 10.2. It is noteworthy that he concludes that certain forms of flaking usually interpreted as evidence for advanced forms of mental "planning" are also open to rather simpler interpretation in terms of relatively "mindless" linking of algorithms.

Whereas Moore draws quite heavily on a psychologist's (Greenfield 1991) analysis of strategies children use in organizing action sequences, the contribution from Wynn and Coolidge (Chapter 5) clearly goes further by articulating a detailed and specific analysis that maps what is known about Levallois reduction onto specific components and capabilities in mental architecture. In short, it represents a theory that maps from attributes of behavioral architecture onto a subset of mental architecture. In doing so, these authors draw heavily on a blend of psychological theories. These address expert performance, working memory, and long-term memory, as well as executive functions. Wynn and Coolidge rely in particular on Ericsson and Delaney's (1999) theory of expert performance in modern humans. The level of expertise in focus is that exhibited either conceptually by chess masters or practically by highly skilled artisans such as blacksmiths. Their somewhat controversial claim is that the cognitive organization of the Levallois procedure is indistinguishable from the cognitive organization of modern technical activities. As with Moore's analysis, hierarchical structure in the action sequence is emphasized along with attention to cues such as distal convexity. Based on Schlanger's (1996) analysis of Marjorie's core, they seek, from a cognitive perspective, to identify specific cues for a "retrieval" structure in the phases of the reduction sequence. Their interpretation has several facets. It is one in which visual cues ("requirements" in information processing) facilitate recognition and guide action selection with no necessary requirement for a mental template. It is also an interpretation that invokes not just the retrieval structure of long-term working memory but also the active attention of immediate working memory to keep "goals in mind."

Wynn and Coolidge also note many similarities between Levallois reduction and chess expertise, as well as a number of differences, and they raise key points of debate concerning the roles of observational learning, theory of mind, and the possible use of language as support for the transmission of complex skills. They adopt what they describe as a conservative stance, arguing that the learning of the Levallois procedure would have been difficult without joint attention, but it possibly did require some theory of mind but not necessarily language. Having addressed the Levallois procedure, they then focus on biface production in the Acheulian, drawing on evidence of refits from Boxgrove. Here, they argue that the level of expertise was different, being organized into fewer routines and subroutines. The overt interpretation is that these required less long-term memory capacity and less time to learn. They also argue that biface reduction would *not* have occupied all the knapper's working-memory resources, allowing sufficient space for monitoring for the presence of useable flakes—a second goal presumed to be held in active working memory.

The claims made for long-term working memory are in many respects far more speculative and arguable than those advanced by Moore. However, the work of Wynn and Coolidge, both here and elsewhere (e.g., see Coolidge and Wynn 2005), is of key importance in that it explicitly seeks to develop links between what we currently know about behavioral systems and the current body of knowledge in psychology concerning mental architecture. It directly addresses the intricacies of the horizontal mappings in Figure 10.2. In elaborating the links they take the important step of seeking to take into account multiple aspects of mental architecture (here long-term memory, working memory, executive function, and attention). In this respect, their approach is "relational" in that it examines multiple facets of the operation of mental architecture rather than focusing on isolated parallels with properties of a specific mental capability such as language. Although I may personally adopt a different perspective about how mental resources are organized and how those resources evolved over time (e.g., see Barnard et al. 2007), I share the view that attempts to map mental architecture onto ideas about tool making and use will only make useful progress if we seek to specify the elements of mental architecture in the kind of detail attempted by Wynn and Coolidge—and then argue from a systems perspective about how that relates to the evidence. It is the method adopted for mapping that is important here rather than whether the individual claims themselves are likely to be sustained over the longer term. Note, for example, that the most controversial claim made by Wynn and Coolidge—that the cognitive organization of the Levallois technique can be equated with the cognitive organization of modern technical activities—implies that there must be resources in mental architecture that have the same attributes in modern and extinct species as well as those that differ. Part of the wider challenge is to develop logical grounds for determining the sets of attributes that are most likely to have been shared and how to distinguish them from those for which a clear case can be made for uniqueness in modern humans. Another challenge is to develop and evaluate formal mechanisms that account for the commonalities and differences in mental architecture over the evolutionary trajectory (e.g., see Amati and Shallice 2007; Barnard et al. 2007).

Whereas Wynn and Coolidge focus on the mental capabilities and requirements that need to be met in the sequence of Levallois reduction, the contribution from de la Torre (Chapter 3) examines the production of earlier Oldowan stone tools. His contribution not only makes use of a comparative evaluation of the nut-cracking behavior of chimpanzees, but it also examines recent evidence that the form of Oldowan tools is more intricate than received wisdom about their rather crude form. An important position in the literature is that the mental architecture of chimpanzees is essentially comparable on key dimensions with that of early hominins (e.g., McGrew 1992). What de la Torre identifies is a range of attributes that appear to distinguish the methods used and artifacts produced by chimpanzees from those evident in the Oldowan. He focuses in particular on the discovery of the conchoidal fracture. Chimpanzee nut-cracking behavior relies on percussion processes, whereas the evidence suggests that those of the early Oldowan represented knapping activities of a qualitatively different form with technological characteristics far more complex than previously assumed. In the latter case, selection of suitable raw materials is taken to imply knowledge of the conchoidal fracture, the capability to rotate and implement sequences of core reduction. All of which led de la Torre to suggest that Oldowan knapping involved sophisticated control of stone fracture and systematic reduction strategies rather than the expeditive smashing of small cores.

From his marshalling of evidence, de la Torre reasons that at least some of the cores and flakes made by early hominins required complex mental capabilities, including abstraction, planning, flexibility, and improvisation, as well as mechanical skills in motor control, precision grip, and marksmanship. He argues that few of these traits are found in chimpanzees. One question that clearly arises from this comparison is whether we can think of a macrotheory of mental architecture that would be of the same basic class while allowing for the differences observed between chimpanzees and Oldowan tool makers? Most of the key features of contrast involve purely spatial-praxic skills. These could simply have been more extensively differentiated in earlier hominins than in extant chimpanzees, but with the same basic mental architecture. This would represent a case where a mental architecture with the ability to represent and mentally manipulate spatial-praxic abstractions was at a more advanced stage of behavioral exploitation of this class of capability than that achieved in chimpanzees. In principle, two mental architectures can have the same basic organization of components but nonetheless show greater differentiation in the range of behaviors they support (Barnard et al. 2007). None of the evidence addressed seems necessarily to imply a requirement for anything other than specifically spatial-praxic abstraction. The possible exception is the implication that the production of at least some Oldowan artifacts involved a degree of planning and flexibility not shown by chimpanzees—but even here, the work of Moore (Chapter 2) reminds us that behaviors that appear to imply mental complexity can readily arise as an emergent property of the use of really quite simple algorithms. In this respect, the conceptual framework shown in Figure 10.2 allows for chimpanzees and early hominins to have the same basic architecture of mind at the level of how it is configured, while differing in capabilities expressed and how the requirements are met for those capabilities to be used.

Two of the other contributions to this volume, those of Wurz (Chapter 7) and Kuhn (Chapter 6), focus less on the component aspects of mental and motor skills and more on what the form of stone artifacts implies for the cognitive capabilities of those who made and used them. Whereas Wurz focuses on symbolism, an ever-present theme in debates about our own uniqueness when compared to precursor species, Kuhn critically evaluates what the form of stone tools implies for the issue of whether the tool makers intentionally imposed form on the artifacts they made. Both contributions make extensive use of statistical analysis of variation in the morphology of artifacts in an effort to understand what could have given rise to such forms.

Wurz opens her contribution by succinctly reviewing the key issues that have been widely addressed in the extensive literature on symbolism and its links to language evolution, neural mechanisms, and artifact manufacture. Her analysis, focused on the evidence from Klasies River, then goes on to demonstrate the presence of systematic changes in artifact manufacture over time with long, thin blades and points in quartzite during in MSA 1 that are thin relative to piece length and involve intensive preparation. Those of the overlying MSA 11, produced using a unipolar Levallois technique, clearly differ, with shorter points and blades that have thicker platforms. The subsequent Howiesons Poort phase is indicative of a similar reduction strategy to that of MSA 1 but relies on distally sourced raw materials knapped into short, thin blanks for the production of backed artifacts. These and other variations noted by Wurz are interpreted as stylistic changes. Possible "strong" causal accounts, such as styles that are behavioral responses to changes in climate and allied adjustments to foraging strategies, are argued to be best approached with some caution. Similarly, it is noted that such stone artifacts are, at best, ambiguous indicators of behaviors that are grounded in symbolic behavior. The key message is that patterning must be interpreted in the context of other types of evidence, such as the presence of beads or markings at the same or earlier periods, reinforcing a requirement to take wider perspective on a whole behavioral system rather than an isolated component of it. Changes over time, not only within an artifact type but across types, are needed to establish exactly what kind of behavioral architecture is in place and what that architecture implies for mental architecture. Indeed, Figure 10.2 implies that we need to address at least three aspects of "symbolism." One relates to what form of physical interactors implies communication among agents in a behavioral system; another relates to the possible presence of a distinct semantic representation in mental architecture; whereas the third relates to how we can best map between the two.

Kuhn shares with Wurz a concern about what morphological variation implies for the set of capabilities in mental architecture and draws a clear distinction between morphological standardization in the final form of artifacts and those relating to the kinds of procedural standardization that form the basis of Moore's (Chapter 2) characterization of artifact architecture. Kuhn critically evaluates two features of arguments about morphological standardization, with one issue being definitional. He notes that the whole notion of standardization can be taken to conflate observations about morphological variation with the ultimate cause of that variation. The second concern is with the ways morphology is assessed, emphasizing the need to rely on quantitative methods. Of central importance in wider debates about the attributes of cognition in precursor species is the extent to which we can infer whether particular species recognized particular forms as in some way special and/or intended to impose particular forms on the stone artifacts they created. Several arguments have been well-rehearsed, including the idea that the final form of an artifact is a by-product of a process and fracture dynamics rather than an "intended design" (e.g., Davidson 2002).

Kuhn impressively uses statistical analysis to examine variation and the possible origins of that variation. Standardization may appear in the record partly because the space of possible forms is not as large as might be assumed. When plotted in three dimensions (length, width, thickness), Levallois points appear to form a clear cluster, but Kuhn's analysis reveals that a great deal of the possible space could not physically exist or is one where any products would not have been classified as Levallois flakes, however they might have been produced. Statistical coefficients of variation are also extremely revealing. Comparison of flakes, sidescrapers, and cores from two Mousterian sites on statistical grounds indicates that the similarity, for example, among cores is not a function of their classification but almost certainly the product of the technological constraints of the particular reduction strategy used. For an experimental psychologist like me, Kuhn's conclusion that the data necessarily cast considerable doubt on the reliability of mapping redundancy of form onto claims about the imposition of design standards on the final products is particularly persuasive. Furthermore, his proposal that it may be profitable to study errors in tool manufacture as a means to better understand the "goals" of a particular knapping episode is also to be welcomed since both quantitative and qualitative attributes of errors are taken in psychology to be key indicators of the basis of a skill as well as its level of development. Kuhn's arguments, in some respects like those of Wurz, remind us that mapping evidence from the traces of behavioral architecture onto properties of mental architecture requires not only the elimination of alternative explanations of standardized form but also exploration of what might have governed errors, selectivity in material choice, and so on. As with Figure 10.2 and the idea that four classes of constraint determine behavior trajectories (configurations, capabilities, requirements, and control and coordination), the force of what Kuhn is saying seems to imply that our focus might better be placed on evaluating systems of constraints rather than simple mappings from an attribute of an isolated "interactor"/tool to an equally isolated attribute of capability in mental architecture.

Both Stout (Chapter 8) and Davidson (Chapter 9) in their respective contributions address possible relationships between language and the manufacture of stone tools. Stout highlights three possible domains of enquiry in which it can be productive to consider relationships between language and tool use. Each relates to a different level of systems description of the form shown at the outset in Figure 10.2. One area addresses the possibility that the two skills may share common neural substrates (neural architecture), another is that of shared social context (interactions in behavioral architecture), and the other that they may both rely on general cognitive capacities such as working memory (mental architecture). There is much to debate here and the exposition itself illustrates many of the challenges that need to be addressed when filling out the "web of inference" represented in Figure 10.2, requiring consideration of how various micro-theories interrelate within a macrotheory at any one level of system description, as well as how we might best map between different levels of system. To take just one example, research by Stout and Chaminade (2007) used positron emission tomography to examine brain activation of novice knappers before and after four hours of training in the production of Mode 1 flakes. This was compared with patterns of activation in a control condition where cobbles were simply bashed together without attempting to produce flakes to assess activation allied with simple object manipulation and percussion. The difference between activation patterns indicated that knapping relies on a parietal frontal network, one component of which (the ventral premotor cortex) is a major potential locus of overlap with parts of the neural substrate for language and may relate to "mirror neurons" implicated in action understanding, whereas another component of the network activated (the anterior intraparietal sulcus) is believed to play a key role in visually guided grasping. Such findings and observations are immediately engaging and clearly require further exploration, but we need to remember two things. First, the mental architectures in the scanner are those of thoroughly modern humans whose brain networks underlying those mental architectures have large-scale connection pathways that are much more pronounced than those of, for example, macaque monkeys (e.g., see Aboitiz et al. 2006). Second, much remains to be understood about how different patterns of connectivity emerged in evolution and how they influence regional patterns of activation. A well-developed system-level understanding of the mutual interdependences of "interactors" in human brain architecture remains to be elaborated, and we have no way of knowing about the internal configurations of connectivity in hominin brains.

In spite of this, convergent evidence for some form of connection is instructive. Stout also draws on several types of observation about how shared social context in behavioral architecture may facilitate skill acquisition, noting that refinement of knapping skill across the archaeological record along with gesture and vocalization are used by modern knappers to combine and shape behaviors. Socially facilitated skill learning over successive generations would contribute to fitness benefits allied to any intentional vocalization and proto-linguistic communication. Another feature of the comparison between the neural substrates of language and tool making concerns the inferior frontal cortex and the possibility that this supports working memory and hierarchical, cross-modal unification of the kind that would be required in more complex tool manufacture. Differences in prefrontal activation were not observed for Mode 1 knapping, but a key prediction, and an important consequence of this analytic perspective, is that any knapping process that requires higher-level organizations of actions or the more intricate hierarchical structures described by Moore (Chapter 2) should lead to more extensive activation of frontal regions. One important concern here is that alternative scenarios need to be clearly laid out for comparison. If, as Wynn and Coolidge (Chapter 5) suggest, certain forms of tool manufacture rely on long-term working memory, then that too may have different implications for the patterns of regional brain activation to be expected. It is also of note that, as with the methodological concerns underlying the interpretation of standardized tool form documented by Kuhn (Chapter 6), methodological concerns equally arise in the interpretation of the results of brain imaging. These methods often rely (as did Stout and Chaminade 2007) on subtractive statistics. The absence of a difference in frontal regions between percussion and knapping does not exclude the possibility that other subtractive comparisons would reveal either consistently high or consistently low levels of frontal activation in the task conditions compared. It is also worth noting that we can learn as much about the workings of brain mechanisms by exploring those areas where there is significant deactivation.

Davidson (Chapter 9) addresses the central question for the whole volume—what cognitive abilities are implied by the manufacture of stone tools—alongside a second key question concerning the sort of selective environment for the evolution of cognition that was provided by the requirements of making those tools. Like de la Torre (Chapter 3), Davidson initially compares the tool-making activities of chimpanzees with the activities of hominins. Once again important differences emerge—such as the idea that cutting was a significant innovation of hominins and that the cores and abandoned flakes created a new environment of opportunity. In the latter case one of several key differences is that abandoned knapping floors represent a new source of stone raw material. He also draws on some of our own joint research concerning possible precursors to fully developed human semantics (Barnard et al. 2007; Byrne et al. 2004). Semantic case roles are implicit in the behavior of chimpanzees in a way that does not imply advanced cognition in and of itself. What Davidson notes is that several semantic case roles are associated with the generation of physical products and that this provides exactly those conditions where hominins could learn about regularities not just about action but of more abstract properties that related actions have in common.

Davidson also adds to the picture of changing cognition by examining parallels among Jackendoff's (2002) hypothesized stages of language evolution (expletive use linked to emotion, a symbol stage, a symbol-construction phase, and a phrase stage). He speculates about the sorts of archaeological signatures in tool use that might correspond to these phases. Arguably, the expletive or one-word phase finds equivalents in chimpanzee tool making for termiting and the earliest forms of stone tools. The cognitive processes involved in the latter may provide the basis for more productive use of stone without the specific mechanism. Likewise, he raises a number of suggestions and counterarguments to them for parallels in Jackendoff's scheme for the subsequent three phases. For example, useful parallels with Jackendoff's fourth phase may only be present very late in the record with the arrival of composite materials, hafting, and the construction of watercraft that must have been used to colonize Australia. But Davidson notes that if composite technologies really are analogous to the final "Phrase Structure" phase in this scheme, then it might lead to the conclusion that language emerged in Europe. This poses something of a problem since key examples predate the appearance of modern humans in that location. That in turn would create the paradox that the most distinctive aspect of modern human behavior would have to have emerged in more than one species of hominin in more than one region. If we briefly return to the idea that mental architecture is composed of a number of basic interactors (Figure 10.2) that are specialized modules working in different domains, then we need to proceed cautiously with this sort of parallel. At least in some proposed mental architectures, features such as the capability to reorder elements of mental representations in the domain of spatial-praxic abstraction can be argued to have emerged earlier than reorderability in the domain of auditory-verbal abstractions (Barnard et al. 2007). From this viewpoint, there may well be parallels between what underlies tool making and language use, without any necessary temporal coupling.

One aspect of the manufacture of stone tools that is frequently noted concerns how little actually changes in the tool-making record over the million years following the appearance of *Homo erectus*. The contribution to this collection from Nowell and White (Chapter 4) is distinctive in two ways. First, it reexamines the middle Pleistocene by drawing on data that tell us something about the significant changes in the life history of these hominins that occurred around this time. Second, it takes up the challenge of reevaluating the apparent stasis in Acheulian tools by considering the distinction between inventiveness and innovation. Clearly, many interlinked facets of hominin life history changed at the beginning of the Middle Pleistocene. The evidence suggests a substantial shift away from earlier pongid patterns with changes in gait, diet, and brain size; extensions of ranges; and changes in reproductive patterns, alongside more extended childhoods and perhaps allied changes in infant-rearing practices. To accommodate all of this, we can only infer that there must have been considerable adaptation in the properties of "behavioral architecture" with capabilities, requirements, and patterns of behavioral control and coordination all being subject to adaptation. Whether this was necessarily accompanied by some deep alteration in mental architecture is clearly a key issue to be addressed. If there were a decoupling between life history and the technological system in place, how would we explain it?

Nowell and White point out that following the initial surge of technological change, the adaptations were perhaps sufficient to support, and flexible enough to sustain, the lifestyles of these hominins with little in the way of selective pressure for further advancement in mental capabilities. Precocious innovations appear at best to be short-lived. Even if small steps in cultural innovation were present, modeling suggests that populations were too small for enduring change to take place. Perhaps there were just too few mechanisms for change to spread beyond a group, and any mechanisms for transmission in the Acheulian were passed from parents to offspring rather than between groups. When changes in life history are factored in, Nowell and White note that the small, intimate, and affective networks that have been envisaged for these hominins (Gamble 1999) could well have created social conditions that channeled behavior into a restricted repertoire of simple elaborations and refinements of existing skills. What this chapter puts before us is not the advocacy of a particular answer to any decoupling of life histories and technological patterning, but the challenge of developing alternative accounts of it.

Like many other contributions to this volume, key aspects of Nowell and White's observations highlight the need to consider how multiple constraints determine what goes on in a complete behavioral system, extending beyond those introduced at the outset of this commentary and intersecting with many types of systems analysis. I conclude this commentary with three personal observations. First, interrelationships most often appear in the literature using the language of "convergent evidence" for particular positions, and these are frequently brought into play in arguments where evidence is sparsely distributed. It is not uncommon for such evidence to be recruited in a somewhat ad hoc manner. I personally wish to see the field move one stage further and explicitly seek to position converging lines of evidence in terms of a meta-framework for inference of the sort suggested in Figure 10.2 and the discussion of it. Second, although emotion or affect has received some brief references within this collection—as with Davidson's noting of the possible part played by affect in the earliest phases of language evolution—its wider role across the hominin evolutionary trajectory is a topic of particular interest to me, and I advocate further discussion of possible linkages among tool use, affect, and the evolution of fully modern ideation in all its aspects. Such a move would seem to be a requirement if we are to develop proper macro-theories of the evolutionary trajectory that ultimately led to the emergence of *Homo sapiens*. Likewise, although several ideas are in play relating adaptive behaviors to "standard" evolutionary mechanisms of selection, in my view, there is a pressing need to develop our understanding of mechanisms through which mental architecture might have differentiated in a coherent sequence all the way from our last common ancestor with great apes through to the emergence of our own species (see Amati and Shallice 2007; Barnard et al., 2007) and also to relate that to what we know about the use of tools by hominin and non-hominin species.

In closing, as an experimental psychologist, I hope that those more conversant with the evidence base and methodologies of cognitive archaeology will forgive any misinterpretations of the material I have commented on here or where I have omitted addressing issues that they would like to have seen more in focus. Finally, the chapters brought together in this collection capture many different facets of the development, manufacture, and use of stone tools. They also capture something of the intrigue, excitement, intellectual conflicts, and deep challenges of interpreting one of the sources of hard evidence concerning the progression of mental capabilities from early hominins to fully modern humans. Multiple perspectives on the activity of making stone tools, coupled with conjectures concerning other key domains of mental life such as joint attention, pattern recognition, use of memory, and the emergence of language, provide an intellectual setting in which convergent lines of argumentation play an essential role in seeking to chart possible trajectories followed as the cognitive capabilities of our distant ancestors successively advanced. Properties of brains and minds that have the ability to grasp and capitalize on the significance of pattern in material in creative ways, as well as the cultural implications of the transmission of these skills, all figure as means to the end of developing an understanding of how our more advanced cognitive capabilities came to be as they are today. We look forward to how this field evolves as more evidence and arguments are brought into play.

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