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Materiality and Human Cognition

Karenleigh A. Overmann[*] and Thomas Wynn

Center for Cognitive Archaeology, Department of Anthropology,
University of Colorado, Colorado Springs

In this paper, we examine the role of materiality in human cognition. We address issues such as the ways in which brain functions may change in response to interactions with material forms, the attributes of material forms that may cause change in brain functions, and the spans of time required for brain functions to reorganize when interacting with material forms. We then contrast *thinking through* materiality with *thinking about* it. We discuss these in terms of their evolutionary significance and history as attested by stone tools and writing, material forms whose interaction endowed our lineage with conceptual thought and meta-awareness of conceptual domains.

Keywords: materiality, writing, stone tools, cognitive evolution, Material Engagement Theory

In a recent science-fiction movie (Villeneuve, 2016; also see Chiang, 2002), humans learn to communicate with an extraterrestrial species. The plot draws upon ideas from neuroscience and linguistics to suggest that immersion in the alien language would change how humans perceive time: acquiring a second language involves neural change (Abutalebi, 2008); language influences or determines thought (Sapir, 1929; Whorf, 1940); language affects how time is conceived (Whorf, 1950). In emphasizing the consequences of mastering an alien *language*, however, an important point is conspicuously missed: The characters also interact with an alien *material culture* (i.e., its writing). While the time-travel effects that result are the stuff of fiction, the idea that brains can be changed by interacting with material forms is not. Rather, it is both something we do every day and implicit to our evolutionary history. For example, learning to read and write is an interaction with a material form that changes functionality in the fusiform gyrus (the part of the temporal lobe that recognizes objects), Broca's and Wernicke's areas (the main centers for producing and comprehending language), and Exner's area (the part of the brain active in handwriting) (Overmann, 2016a). The Neolithic peoples who first realized literacy from the behavior of writing adapted a material form that would eventually yield unprecedented access to and meta-awareness of human conceptual domains (Olson, 1994; Olson & Cole, 2006; Watson & Horowitz, 2011). And species who were our remote ancestors interacted with stone tools in ways that may have produced conceptual thought in the first place (Coolidge & Wynn, 2018).

Materiality's influence on human cognition far exceeds its acknowledged role in offloading and storing mental content (d'Errico, 1998). This is not often recognized, for reasons that include the incremental pace and long temporalities involved in co-influential change between brains and material forms. Here we examine what changes in the brain when it interacts with material forms like writing and stone tools, what it is about such material forms that can cause the brain to change,

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[*] Correspondence concerning this article should be addressed to Karenleigh A. Overmann, Center for Cognitive Archaeology, Department of Anthropology, University of Colorado, Colorado Springs, 1420 Austin Bluffs Pkwy, Colorado Springs, CO 80918 USA; e-mail karenleigh.overmann@keble.oxon.org.

and how long it takes brains to reorganize when they interact with these forms. We consider the kind of theoretical framework needed to analyze co-influence between brains and material forms. We discuss *thinking through* materiality (i.e., incorporating it into our cognition; adapting it through long-term use to become increasingly efficient at eliciting specific psychological, neurological, and behavioral responses; and using it to recreate those changes in newly indoctrinated individuals; Overmann, 2017) and why we often fail to notice its role in cognition, effects of embodied skill and behavioral automaticity that free up attentional resources for other purposes. We contrast *thinking through* materiality with *thinking about* it (i.e., forming and manipulating concepts) and explain why *thinking about* materiality is both wonderful and strange from an evolutionary perspective. We end by reviewing aspects of the archaeological record that suggest the emergence of these abilities: stone tools and writing, the two material forms that have arguably had the greatest influence on the development of the human capacity for conceptual thought.

Investigating co-influence between brains and materiality requires a theoretical framework that puts them together as a system, rather than treating them separately. This perspective is provided by Material Engagement Theory (Malafouris, 2013), a theoretical framework in cognitive archaeology in which cognition is viewed as influenced by being in a body (*embodied*; Lakoff & Johnson, 1999; Prinz, 2009) and situated in an environment (*embedded*; Smith, 1999); as comprising a system that includes the body and materiality as constitutive components (*extended*; Clark, 2008; Clark & Chalmers, 1998); as consisting of the dynamic, transformative interactivity among the components (*enactive*; Hutto, 2013); and as possessing an evolutionary history that continues to unfold (*evolving*; Malafouris, 2015). For its part, materiality is envisioned to influence human behavior and psychological processing (i.e., materiality has *agency*); however, it is also acknowledged to have different capacities, potentials, and mechanisms for influencing brain and body and changing in response to their influence than the other components. Materiality is also seen as having and acquiring meaning in virtue of what it is and what humans do with it (what Malafouris calls *enactive signification*).

Applying Material Engagement Theory starts by viewing human cognition as a dynamically interactive system that includes, in addition to brains, bodies and material forms. A systemic view of visual perception, for example, makes it a cognitive state that emerges from the interaction of material stimuli, neural reactions, and physical movements (Gibson, 1977). Humans alter the system by adjusting its components, typically through behaviors with material forms. We are a species that manipulates material forms to produce specific behavioral and psychological responses. An example of this is music. Players of musical instruments produce sounds that elicit physical and emotional responses in those hearing them. Finally, consider the material forms themselves: They are the result of generations and sometimes centuries or even millennia of cooperative effort that has designed and refine them toward producing specific responses, effort often expended without any guiding idea of the behavioral, psychological, or material changes that might ultimately result. They embody and make available accumulated knowledge that functions to decrease the cognitive effort of future generations (Hutchins, 1995), who need merely learn how to use the object (i.e., not reinvent it from scratch), and perhaps extend its application and refine its design.

Material forms and the body are not just causally linked but constitutive of cognition (Malafouris, 2013). Reading is a good example of this, as it is a cognitive state that requires a material form, writing, and the behaviors and neural reactions occasioned by its engagement. Indeed, beyond the neural activity occurring in the brain, without words on the page and the eyes' movements over them, a person cannot be said to be reading. Similarly, in stone knapping, the "decision about where to place the next blow, and how much force to use, is not taken by the knapper in isolation; it is not even processed internally. The flaking intention is constituted, at least partially, by the stone itself ... [which], like the knapper's body, is an integral and complementary part of the intention to knap" (Malafouris, 2010a, p. 17). As reading and knapping cannot be reduced to neural activity, nor writing and stone to perceptual stimuli, it is through the active engagement of materiality that such cognitive states are brought forth and the agency of bodies and material forms revealed. However, we grant there are differences in the degree and kind of cognitive contributions made by bodies and material forms: the pen one writes with, and the chair one sits in to write, contribute differently than the written characters produced with them in matters like the amount of sustained attention they receive, the degree to which they engage bodily movement and require embodied skill, and so on.

When a cognitive state at one time (C_1 at t_1) is compared to another at a different time (C_2 at t_2), any differences between the two states imply that the psychological, behavioral, and material components have changed through their interaction. Specific ontogenetic changes in behaviors and brains are associated with literacy (Dehaene et al., 2010; Nakamura et al., 2012). Less apparent on the ontogenetic timescale is change in the material form, something for which multiple generations may be required. For example, over some 1500 years between the mid-4th millennium and 2000 BCE, Mesopotamian writing changed from signs that conveyed semantic meanings through their resemblance to objects into signs that conveyed both meanings and sounds but no longer resembled the objects they once depicted; this change in form was enabled by change in behaviors and brains, and in turn it influenced further change in both—for example, by intensifying the need for formalized instruction and effectively selecting practitioners into specialized communities with distinct identities (Overmann, 2016a). It is in this temporally laden sense that we use the term "co-influence" to describe the ability of material forms to change behaviors and brains. We then use archaeologically attested change in material forms to infer related change in behaviors and psychological processes.

The ongoing change and transformative capacity of neurons, behaviors, and material forms is "metaplasticity" (Malafouris, 2010b). Here we highlight two aspects of this key idea. First, bodily movement is implicit to everything from moment-to-moment sense-making to cognitive change over time. In perception, movement mitigates the fact that unchanging or overly similar stimuli yield desensitization and habituation. In cognitive change, movement affords the continual engagement of and adjustment to the material forms that comprise our cognitive ecologies (Malafouris, 2013). Second, the interactivity of the neural, behavioral, and material aspects of our cognition extends their inherent plasticity beyond the range endowed through mechanisms like genetics or physics. Thus, humans do not create and use material forms because the species has special brains; rather, humans are a species whose cognition has reached its present state by engaging material forms, past and present.

Brain Change, Material Change, and Temporality

Literacy nicely illustrates the kinds of things that can change in the human brain when it interacts with a material form, as well as its potential to function in ways that evolution did not specifically equip it to do. Today when someone learns to read and write, the fusiform gyrus, which has an evolved function for recognizing objects through combinations of their local and global features, becomes trained to recognize written characters through their features (Cohen & Dehaene, 2004;

Vogel, Petersen, & Schlaggar, 2014). It also becomes trained to interact with Wernicke's and Broca's Areas for comprehending and producing speech and Exner's Area for controlling handwriting (respectively, gyri in the superior temporal, inferior frontal, and middle frontal lobes; Pegado, Nakamura, & Hannagan, 2014). The behavioral component, handwriting, improves hand–eye coordination, fine motor control, the ability to recognize written signs, tolerance for ambiguity in their formation, and recall of the written material (James & Engelhardt, 2012; Longcamp, Zerbato-Poudou, & Velay, 2005; Mueller & Oppenheimer, 2014; Sülzenbrück, Hegele, Rinkenauer, & Heuer, 2011), all of which imply neurological change.

Reading and writing are often considered as a mode of language rather than an interaction between brains, bodies, and a material technology. However, the behavioral (production) and material (product) aspects of reading and writing are critical to understanding their effects on the human brain. The material aspect is particularly critical, given the inseparability of looking at written material to understand its meaning and the written form itself. That is, as a cognitive activity, reading does not exist without writing—the letters, syllabograms, and logograms made accessible to vision and touch by material forms like clay, papyrus, paper, computer screen, sign language, and Braille. Someone can recall information gained through reading, but this differs from what occurs when signs on a page are read. Simply, reading is the interaction of psychological processes like vision and language with the material form that is writing through the behaviors like handwriting that interface them.

Today, reading involves a material form that has become highly adept at eliciting specific behavioral and psychological responses in both novice and fluent readers. At writing's origins, however, neither material form nor psychological processing supported literacy in the way we understand it. Neither could there have been any idea of what would ultimately be realized once people began handwriting simple characters with conventionalized meanings. This behavior was transformative, however, as it occasioned change in both the brain processes involved in reading (described above) and the material form instantiating writing (described below). As behavior, writing represented an interaction between psychological processes, the body, and material forms. As a material form, it instantiated sequences and patterns of lines and curves that cumulatively resembled and thus denoted physical objects. These sequences and patterns were visually perceivable objects whose associated cultural and linguistic meanings were intelligible and thus communicable between individuals. In conjunction with material attributes like durability, the communicative value of signs also intensified the behavior, opening up multiple cascading opportunities for further change in brains and the material form.

Adapting early writing into a form capable of communicating language fluently and influencing psychological and behavioral changes efficiently required the participation of many individuals over multiple generations. In Mesopotamia, one of the earliest known independent inventions of writing, it required the participation of enough scribes to administer a state-level bureaucracy and about 1500 years (Overmann, 2016a).[1] Characters drawn by hand (as opposed to being carved, stamped, or impressed) appear in the Ancient Near Eastern archaeological record in

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[1] A similar analysis of the other writing systems thought to represent independent invention—those of Egypt, China, and Mesoamerica—has not been performed. Thus, they cannot presently be quantified in terms of the length of time needed to realize literacy. However, all four independent origins (the three mentioned plus Mesopotamia) were similar in being bureaucratic states, implying a similar production demand i.e., repetition of conventionalized, simple, non-numerical signs by hand at a volume and over a duration of time sufficient to train the fusiform gyrus, garner handwriting effects, adapt the material form, and realize literacy; Overmann, 2016a).

the late 4th millennium BC. Many were pictographs, conveying their meaning through iconic resemblance (as a picture of a jar meant a jar), and some were ideographs, meaningful in virtue of social agreement as to what they signified (e.g., a circle divided in fourths by crossed lines meant sheep or other ruminants). Within centuries, under the production demands of a state-level bureaucracy, written characters started to become less recognizable as the objects they depicted or signified (**Fig. 1**). The loss of iconic resemblance is reasonably attributed to mechanisms that reflect increased skill in handwriting (e.g., biomechanical effectiveness and motor habituation) and training effects in the fusiform gyrus (e.g., recognition of characters through combinations of their local and global features; adjustment to enhance visual discriminability) (Overmann, 2016a). The loss of overt iconicity meant that the features identifying characters and differentiating them from each other were much subtler. Training and practice became necessary to read and produce them; this excluded non-initiates, created communities of specialized practitioners like scribes, and intensified change in the material form of writing and the brains interacting with it.

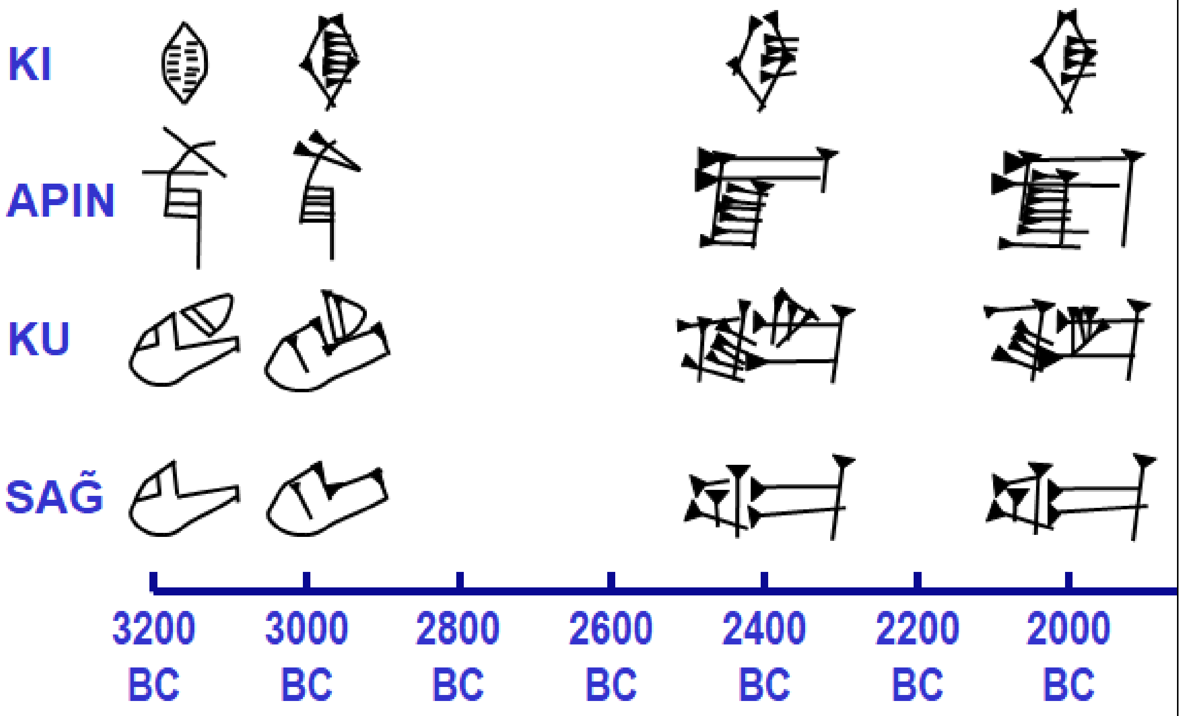

Figure 1. Chronology of cuneiform signs (redrawn from Nissen, Damerow, & Englund, 1993). The early pictures (left) lost their depictiveness somewhere between 3000 and 2400 BC. This change entailed that reading and writing required increasingly formalized training. To highlight similarities, the early signs have been rotated one quarter-turn to the left to give them the same orientation as the later signs (right), which were rotated to the orientation shown between the mid-third and late second millennium, possibly to facilitate biomechanical aspects of writing or visuospatial considerations of reading. Other changes (not shown above) occurred before the script would achieve the requisite fidelity to language needed to support literacy, whose possible onset occurred by 2000 BC (see Fig. 9 in Overmann, 2016a).

Other types of changes (Overmann, 2016a) were required to adapt the initial picto–/ideographs with this-means-that associations between form and meaning into an abstract script with sufficient expressiveness to support a cognitive state analogous to modern literacy. The salient point is that adapting the material form required massive, distributed participation and a cultural span of time. This is significant for two reasons, one trivial and the other not. The trivial reason is that an extraterrestrial material culture would be less likely to interact optimally or immediately with human cognition (i.e., in presumably lacking the requisite participation over sufficient time to become efficient at influencing human change). The important reason is that because it takes massive, distributed participation and cultural spans of time to develop and refine a technology like writing, change becomes invisible, whether the change is material, behavioral, or neural. Each generation merely uses its material culture, and often fails to notice as both it and they change in the process. Material change can represent increased efficiency in changing brains and behaviors. It also represents the accretion of social knowledge, which reduces cognitive effort by distributing past and present effort to the current and succeeding generations (Hutchins, 1995).

Co-influential change between brains, bodies, and materiality occurs on differing but coexisting temporalities, and the longer they are, the less tractable they become to both experience and neuroscience. One temporality is experiential: for example, reading the words on this page. Chances are, most readers do not think of this activity in terms of dynamic, transformative interaction of their psychological processes, behaviors, and a material form. The materiality—words on a page; the page itself; the book containing the pages—seems unchanging. The associated psychological processes and bodily behaviors are mostly unconscious to experience. Another temporality is ontogenetic. Children require several years and specific training to become proficient in reading and writing. The material form of writing as presented to the novice and fluent reader instantiates a spectrum from simple to complex. Change in brain function and form associated with the acquisition of the abilities to read and write can be measured longitudinally, explained theoretically, and appreciated experientially in terms of increased proficiency. Longer still are generational or cultural temporalities. In long temporalities, materiality can change rapidly and profoundly, while accumulating and helping reproduce the incremental changes in behaviors and brains that yield cognitive states like literacy. Over the longest spans of time, which are evolutionary, interaction with materiality has the potential to yield new brain structures (e.g., the regions of the intraparietal sulcus specialized for representing aspects of visual stimuli, proposed to be advantageous in making and using complex tools; Orban et al., 2006). Experientially, the long temporalities are beyond our reach, and neuroscience has at present little theory or methodology to measure or explain them.

Thinking Through and *Thinking About* Materiality

There are other reasons why we might not think of our cognition in terms of incorporating materiality as an integral or constitutive component. Materiality's semiotic value is acquired through enculturation and language, mechanisms that may predominate its acquisition through enactivity. That is, an artifact like a hammer is a hammer not only because its use involves behaviors and linguistic labels that can be learned and reproduced, but also because it is an object that is graspable, movable, and durable enough to be used to beat, drive, or shape other objects (e.g., this enables a fist-size nodule of flint to be a hammer, but not an iPhone). We are consciously aware of very little of our cognitive activity as we move our bodies and interact with material forms. We do not deliberately perceive objects or form memories or think through the moment-to-moment details of how we will move or speak; rather, we perceive, learn, move, and speak without much conscious awareness of the details of the implicit cognitive planning and execution

(Kihlstrom, 1987, 1989). Additionally, behaviors that we may once have been consciously aware to some degree can become highly automated, freeing attentional resources to focus elsewhere. A familiar example of such automaticity is the degree of conscious awareness given to specific movements when learning to drive, compared to the relative lack of conscious awareness given to the same movements once driving proficiency has been acquired (Charlton & Starkey, 2011). In fact, the behavior can become so highly automatized and the use of the material form so unconscious that it is possible to drive to a destination that is familiar but unintended, something perhaps discovered only upon arrival.

Few material devices become a persistent part of the body. Those that do may alter perception and movement: Glasses improve vision; artificial limbs alter mobility, posture, and proprioceptive awareness of where the body is and what it is doing; pacemakers affect the interoceptive awareness of how the body feels, health-wise; and all of them can influence the sense of what the body is, even as they become incorporated to the extent that they receive little conscious attention (de Preester & Tsakiris, 2009). Those material devices that do not become persistent parts of the body—most of the stuff of the environments we traverse and inhabit—nonetheless function to extend the body while they are engaged (de Preester & Tsakiris, 2009).[2] The distinction between prosthetics and body-incorporation and tools and body-extension does not preclude the latter from affecting perception and movement. Certainly, neurons controlling finger movements, for example, react to tools as if they were part of the hand, allowing them to function as extended fingers (Maravita & Iriki, 2004). A stick extends tactile perception along its length to its tip, a phenomenon used by visually impaired people when they navigate by cane (Malafouris, 2008). In a sighted person, visual space is also remapped, so that things within the extended reach of the tool seem nearer to them (Maravita, Husain, Clarke, & Driver, 2001; Maravita, Spence, Kennett, & Driver, 2002). Tools are also subject to effects like automaticity and attentional refocus. In reading and writing, psychological processing, behavioral movements, and the material form become seamlessly integrated, so that the decision to move the eyes over the page cannot easily be separated from the comprehension of what is written on it, or the reading whose feedback facilitates the alteration of both production and written content. Focus on reading content can preclude awareness of the book, especially for proficient readers; when someone is aware of the book, it is probably not being read, as it is difficult to keep conscious attention focused on both book and content simultaneously. Even a material form that can become an integral part of our cognitive system, as a book does in reading, is not experienced as such when it is not so integrated. Materiality becomes merely the tools and objects we pick up, manipulate, and discard to accomplish our goals.

Even if it seems strange to *think through* materiality, let alone do so unconsciously, this in fact may actually be typical of how most species engage material forms in general. That is, organisms may simply perform an action with an object without necessarily *thinking about* the object as something separate from its process of use. This appears to be how non-human primates think with tools: Their focus is on a goal, and tools are a means to that goal but not a separate and

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[2] Beyond common sense, there are few criteria for determining when an object functions as part of the cognitive system. For example, if reading does not exist as a cognitive activity without interacting with the material form of writing, it implies that a book is part of the cognitive system whenever someone is reading it. Its cognitive status while unused but recalled is less certain, its cognitive status unpurchased at a distant bookstore or unfinished by its author even more so. All these connections (and more) can conceivably mean that books are part of the cognitive system, and as concepts, they are certainly anchored by our experience of interacting with books.

distinct goal themselves. But the human ability to *think about* objects—to form and manipulate concepts of them, independent of the processes in which they are used (Coolidge & Wynn, 2018)—is remarkable. It too is arguably part of the ability to recruit and incorporate materiality into the human cognitive system. For example, materiality not only opportunizes the realization of concepts through mechanisms like enactive signification (i.e., things acquire meaning in virtue of what they are as physical substances and how we use them), it also anchors and stabilizes them (Hutchins, 2005), providing the brain with durable, manipulable stimuli. These in turn provide opportunities to realize and recognize new patterns as they are used, organized, and reorganized (Overmann, 2016b). But while even the most purely mental activity may depend on concepts being anchored and stabilized by material structures, such activity can be conducted in the absence of the material structures themselves. And evolutionarily speaking, it is this ability to *think about* materiality that is wonderful and unique to humans.

The role of materiality in human conceptual life may have deep evolutionary roots: Roughly two million years ago, rather than abandoning a tool after use (ad hoc tool use), early members of the genus *Homo* retained and reused their stone tools, demonstrating a new relationship with tools and possibly the beginnings of a concept of one (Coolidge & Wynn, 2018). This does not entail that they had language. Currently, the available evidence has not yielded certainty on when language may have originated. Some estimations have placed it as early as 1.8 million years ago, either in conjunction with the appearance of the Acheulean handaxe, or with early *Homo* (e.g., Holloway, Sherwood, Hof, & Rilling, 2009). The latter has long been associated with KNM-ER 1470, a 1.8-million-year-old *Homo rudolfensis* specimen interpreted as having asymmetry and Broca's cap (Falk, 1987; Holloway, 1983; Tobias, 1981): Asymmetry suggests the neurofunctional lateralization associated with language and handedness, Broca's cap, language.

Such features, admittedly, "cannot prove that this or that hominid had language" (Holloway et al., 2009, p. 1330). Parsimonious interpretation is warranted, for several reasons. First, endocasts provide limited insight into neuroanatomical landmarks and within-species, inter-individual variability. Second, while Broca's area (Brodmann's area 44/45) is expanded in humans, something that is reasonably related to language (Schenker et al., 2009), great apes possess "an anatomical and functional homologue of Brodmann's area 44" (Sherwood, Broadfield, Holloway, Gannon, & Hof, 2003, p. 277). Great ape brains are also asymmetric, at least in captivity, where they may be artificially exposed to greater tool use (and even then, again to a lesser degree than is characteristic of human brains) (Hopkins et al., 2017). Further, Broca's area has been implicated in both language and tool use (Binkofski & Buccino, 2004; Higuchi, Chaminade, Imamizu, & Kawato, 2009). Accordingly, even if KNM-ER 1470 is correctly interpreted as having Broca's area, it remains unclear that the feature would necessarily indicate language in addition to the tool production and use archaeologically attested. Further, a recent experimental study suggests that producing an Acheulean handaxe may be more a matter of fracture mechanics than linguistic instruction or intentionality (Moore & Perston, 2016). Others have not found a strong role for verbal instruction in lithic reduction techniques (Putt, Woods, & Franciscus, 2014), at least until those techniques become more complex than those associated with producing handaxes—for example, prepared core strategies like Levallois (Lycett, 2018). Thus, neither the paleontological or archaeological evidence necessarily demonstrates the availability of language at 1.8 million years ago in conjunction with early *Homo*.

Further, many extant non-linguistic species use ad hoc tools: chimpanzees modify sticks to fish for termites, sea otters crack open shellfish using rocks as anvils, crows use twigs and other materials as probes, and octopuses use coconut shell halves for defense (Finn, Tregenza, & Norman, 2009; Hall & Schaller, 1964; Hunt, 1996; Sanz, Call, & Morgan, 2009). Like these species, early *Homo* too was presumably alinguistic, since they lacked the requisite physiological changes associated with language (e.g., significant altriciality, decoupled respiration, and descended larynx) that would variously appear between 1.8 million to 200,000 years ago with *Homo erectus* and *Homo sapiens*, though these features too may not be dispositive regarding language or its absence (Fitch, 2000, 2009, 2017). The possible appearance of a tool concept prior to language would also be consistent with the mosaic evolution that has characterized evolution in the hominid lineage more generally (e.g., bipedalism occurred long before brain size increased; Lovejoy, 1988).

Even modern humans may form and mentally manipulate concepts in ways that are independent of language but related to motor activity. In reading, activity in Exner's area, a part of the brain located above Broca's area and anterior to the primary motor control area that has been implicated in the production of handwriting (Pegado et al., 2014), is thought to provide "a core recognition of the gesture in the written word" (Konnikova, 2014). Numbers and mathematics provide another potential example, as modern brains performing mathematical tasks recruit neurological circuits involved in planning and executing motor movements (Andres, Seron, & Olivier, 2007; Heimann, Umilta, & Gallese, 2013; Penner-Wilger et al., 2007; Tschentscher, Hauk, Fischer, & Pulvermüller, 2012). This is especially true of the motor control of the fingers, as attested by both lesion studies and performative skills. Damage to the angular gyrus, which has been implicated in finger control, is associated with finger agnosia and acalculia, the inabilities to know the fingers and perform calculations, respectively (Roux, Boetto, Sacko, Chollet, & Trémoulet, 2003). The mental abacus, an imaginary device used to perform complex mathematical calculations with accuracy and speed, demonstrates the importance finger movements (Brooks, Barner, Frank, & Goldin-Meadow, 2014; Frank & Barner, 2012). Interestingly, such motor planning functions take place whether or not the movements are actually carried out—a kind of internal simulation—and this may be the quality that enables individuals with impaired mobility to participate in human conceptual life.

The use of "neural muscles"[3] to manipulate both objects and concepts is also suggested by mirror neurons and cerebellar activity. Mirror neurons, which become active both when an individual performs a motor action and when an individual sees a conspecific perform a motor action, may provide a gestural underpinning for communication with implications for the evolution of language (Gentilucci & Corballis, 2006). However, their presence in non-human species suggests that mirror neurons provide a largely alinguistic basis for understanding conspecific

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[3] Embodied engagement with material objects involves neural activity (e.g., motor planning and execution), and motor planning in the absence of motor execution has been found in mentally manipulating concepts like numbers. It may be implicit to literacy as well, since Exner's area for controlling the movements of handwriting is active in recognizing characters (i.e., reading), as distinct from their manual production (handwriting). We have proposed the term "neural muscle" for this phenomenon. Specific neural activity continues to be elicited by interactions with specific material forms, even as the original motor movements become obsolete and are discarded (e.g., as typing on computer keyboards obviates writing by hand). This suggests that neural activity associated with higher-level cognitive functions may relate to productive behavior with past cultural forms and behaviors (e.g., prehistoric stone tools and their production and use), with descendent interactions with cultural forms and behaviors perpetuating the associated neural responses. Elsewhere, we have proposed the term "neural fossil" for the persistence of "neural muscles" beyond the material forms that occasioned them (though "fossil" has an inapt connotation of formerly and hence no longer living). We propose that humans have developed a generalized neurological response to material culture that is perpetuated by interacting with descendent material forms and behaviors. None of this discussion should be understood as proposing that the neural activity in question is necessarily representational in nature.

motor actions and intent, and these are important in human tool teaching and learning (specifically, the understanding and imitation of behaviors in the absence of verbal instruction). The cerebellum, traditionally ascribed a role in motor learning, fine motor control, and motor movement sequencing, may play an important role in creating and manipulating abstract concepts as well, along with higher-order decision- and rule-making for multiple forms of information (Balsters, Whelan, Robertson, & Ramnani, 2013; Koziol, Budding, & Chidekel, 2010; Vandervert, 2009; Vandervert, Schimpf, & Liu, 2007).

This is not to argue that language is unimportant to concepts—far from it. It is, however, to recognize that the early *Homo* (pre-*Homo erectus*) cannot be excluded from having had the requisite ability to manipulate conceptual objects as if they were physical forms on the basis of not having language. It is also perhaps a reason why the inclusion of multiple material forms, especially novel and unfamiliar ones, can spark creativity (Kirsh, 2014): Not only do novel material forms opportunize the recognition of new patterns, they may also engage distinct neural muscles (i.e., ones that differ from any previously engaged). And it is to the remote past and long temporalities involved in the evolution of our lineage that we must turn to answer the question of when and why these abilities emerged.

The First Stable Category of *Thinking About* Materiality: The Biface

Well beyond the unconventionality of considering the material form of writing as something tractable to archaeological investigation is the problem of discerning the evolutionary shift from *thinking through* materiality to *thinking about* it from the archaeological record. One potential criterion is behavioral change, such as when early *Homo* began to retain and carry flakes and cores from one location to another (Braun et al., 2008). But did this behavioral change entail that early *Homo* also had a concept of tool? How could archaeologists possibly decide, one way or the other? Another potential criterion is artifact type, the idea that tools can be categorized by form, with the archaeological recurrence of a particular form suggesting both intent and a concept of form on the part of those who recreated it. The idea of artifact type, however, is something with which archaeologists have long struggled. That is, there are almost no ways to confirm how well and in what sense our categories of archaeological analysis correspond to categories recognized by prehistoric humans, especially for the very deep past. Of course, there is no requirement that there be any such correspondence, for archaeologists often employ analytical types to help them investigate the past, without any need for analytical categories to reflect ancestral ones (assuming early hominins even had the ability to categorize to begin with) (Dunnell, 1971). But if archaeologists could identify categories used by early hominins, it might reveal something interesting about how and when a tool concept first emerged.

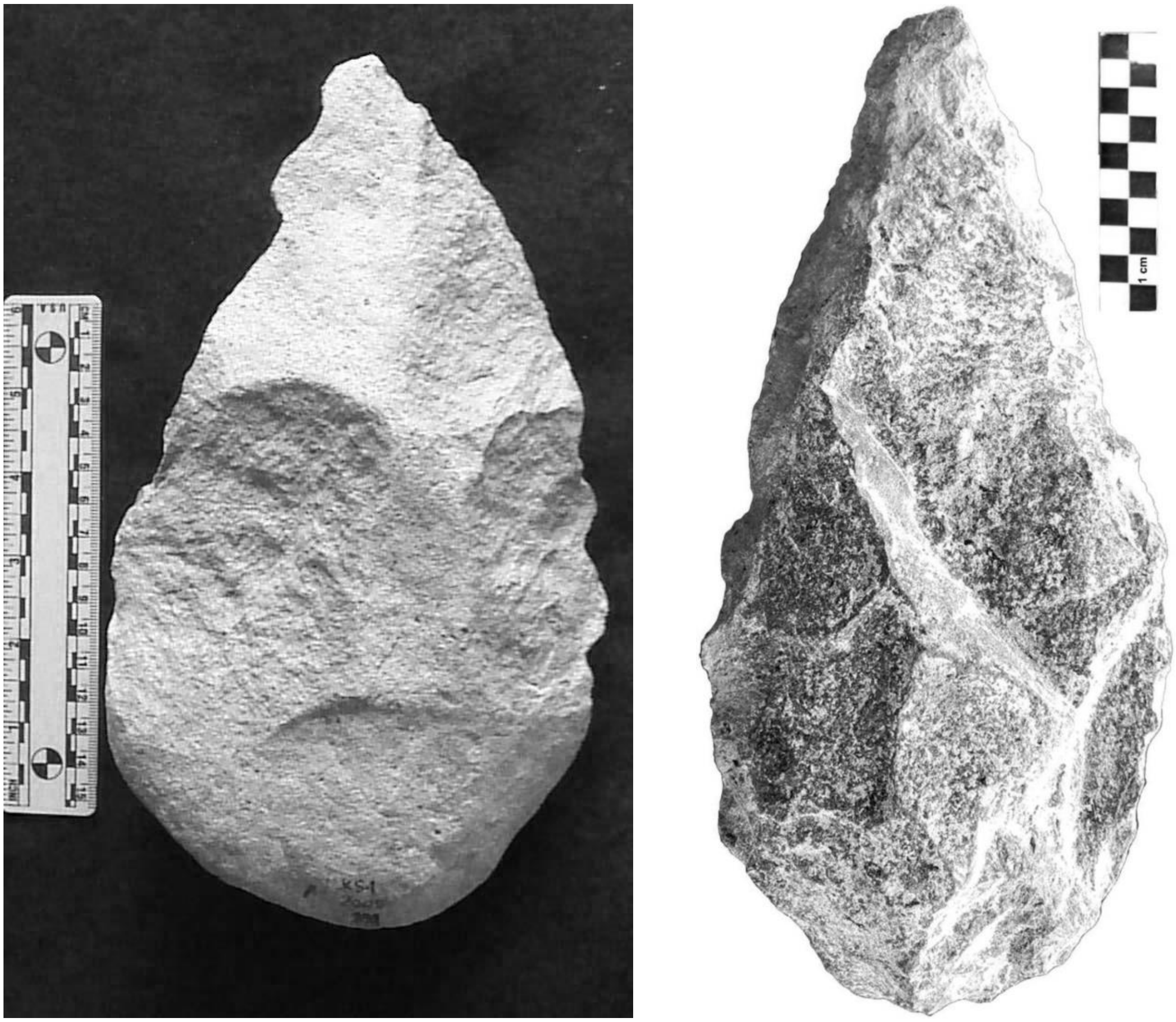
Archaeologists no longer believe that the earliest stone tools were organized into natural categories or types (Toth, 1985; Wynn, 1981; Wynn, Hernandez-Aguilar, Marchant, & McGrew, 2011). Instead, the earliest lithic assemblages are thought to be the result of hominins focusing on task completion and producing a series of temporary products along the way. Many archaeologists suspect that the first imposed artifact categories appeared about 1.8 million years ago in the guise of tools known as bifaces, often also referred to as “large cutting tools” (LCT). With these tools, hominins for the first time manufactured material objects that seem to clump into categories. Glynn Isaac once used the metaphor of a spatial surface to describe the variability of early Paleolithic stone tools, with high points on the surface representing distinct design targets (Isaac, 1969, 1976).

The implication of Isaac's analysis was that the hominins themselves would have recognized these peaks in morphological space as differentiating distinct categories of tools. If these hominins were in fact *thinking about* their tools, then they very well could have thought of them in terms of these morphological categories. But how did these hominins generate these categories in the first place?

Fig. 2a is an image of a handaxe excavated at the 1.79 million-year-old Kenyan site of Kokiselei (Lepre et al., 2011). Archaeologists now use the typological term *biface* or *large cutting tool* for the general category, and *handaxe* for the narrower category that encompasses bifaces whose sides converge on a pointed tip, such as the example in **Figs 2a** and **2b**. These different terms reflect a century and a half of uncertainty about what such artifacts may have represented as cultural products, and indeed, whether they could rightfully be described as cultural products in the first place. The best recent description of a biface is that of John Gowlett (2006; Wynn & Gowlett, 2018). He began his definition of a biface with a basic core chopper, a variety of temporary core tool that hominins began using about 3.3 million years ago (Harmand et al., 2015). He then asked what hominins added to the basic chopper to produce a large cutting tool such as a handaxe. Gowlett proposed six essential characteristics, which he termed "design imperatives":

1) Glob-butts: For a tool to be an effective hand tool, it needed a center of gravity that fit in the hominin hand. The solution was to retain a mass of stone, often unmodified, that allowed the tool to fit comfortably in the hand; this feature also provided sufficient weight to enable the tool to function.
2) Forward extension: When making handaxe, the tool maker's primary goal was to produce a cutting edge that was longer than those on a core chopper, as well as to acquire greater leverage. Knappers accomplished this by extending the length of the tool as measured away from the palm and the center of gravity.
3) Edge support: The primary functional feature of a handaxe is a cutting edge. The sturdiest edge is a bifacial edge. Hominins produced this by removing trimming flakes from the edge onto both faces of the tool. This produces an edge that has an effective cutting angle that stands up to repeated use.
4) Lateral extension: A long, narrow tool with a glob-butt and long cutting edge will tend to twist in the hand. To counter this tendency, hominins retained as much breadth as possible, especially at the glob-butt end of the tool.
5) Thickness control: Lighter tools are easier to wield, and cause less fatigue. The hominins strove to reduce the thickness of their handaxes in order to reduce weight. With the constraints of forward and lateral extension, the only avenue for weight reduction was via thickness, especially toward the working end of the tool.
6) Skewness: When the center of gravity was slightly off-center, the result was a tool that was better balanced for single-hand use.

If a hominin tool maker deployed these considerations when making a large cutting tool, the result would be what we see in **Fig. 2b**. All these considerations are ergonomic: They instantiate the basic physics and perceived muscle and skeletal resistances of a hand-held tool. These are embodied resources, and thus the advent of biface technology arguably occurred through developments in embodied cognition. But the question at hand is the development of categorical thinking, the ability to *think about* materiality. In what sense did these design imperatives constitute an ontological category of tool?



(a) (b)

Figure 2. Handaxes. **(a)** Left: Handaxe from Kokiselei, Kenya, ca. 1.76 million years ago (Lepre et al., 2011). **(b)** Right: Handaxe from FLK West, Olduvai Gorge, *ca.* 1.69 Ma (Diez-Martín et al., 2015). Though only 70,000 years apart, the FLK West handaxe (right) differs from the Kokiselei example (left) in its size, symmetry, and manufacture technique, suggesting its production involved greater attention to features of the tool.

Cognitive science has long been interested in categorical thinking. Historically, two models have dominated. Advocates of one argue that the mind defines categories through a list of required features; an exemplar qualifies for membership in a category if it presents all of the required traits, or in some versions of the model, a preponderance of required traits (Barrett, 2017; Carey, 2009). For the second model, the prototype, an exemplar warrants inclusion in a category based on its degree of resemblance to a prototype, something presumably held in long-term memory. After decades of debate and experiment, cognitive science has resolved the debate in favor of the prototype model: “The existence of prototypicality structure and its importance in the process of categorization are absolutely beyond doubt” (Carey, 2009, pp. 496–497). However, there remains uncertainty about how the mind generates prototypes and how an individual learns them. In some situations, it appears that individuals rely on memory of specific exemplars as prototypes, while in others individuals generate a kind of average “family resemblance” from the metaphorical range of variation of exemplars (Palmeri, 2014; Smith, 2014). In the kinds of natural settings that primates encounter daily, the “family resemblance” solution appears more efficacious than reliance on specific exemplars (Smith, Zakrzewski, Johnson, & Valleau, 2016).

From the perspective of grounded cognition (Barsalou, 2008) and Material Engagement Theory (Malafouris, 2013), categories emerge when bundles of co-occurring embodied and extended traits coalesce into a prototype, a variety of “family resemblance” based in neuromuscular, ergonomic, and visual experience. This requires two cognitive processes: attention and association. Categories emerge “when attention is focused repeatedly on the same kind of thing in the world, by utilizing associative mechanisms among modalities, which, in turn, might permit re-enactment and simulation” (Pezzulo et al., 2011, p. 6). This is how a child learns categories: repeated association of salient features in attention, followed by simulation and internal execution of the associated bundle. Note that such categories are not abstract in the usual sense of the word, and need not exist as mental templates or visual images, though visual features can certainly be features of prototypes. At the evolutionary scale of change, the co-activation of perceptual features of tools and the motor component of tool use engage the appropriate neural resources (neuronal recycling; Dehaene & Cohen, 2007) and initiate neural reorganization via Baldwinian natural selection (Wynn, Overmann, Coolidge, & Janulis, 2017), which holds that “under some conditions, learned behaviors can affect the direction and rate of evolutionary change by natural selection” (Depew, 2003, p. 3).

There is an interesting irony here for archaeologists interested in stone tool typology. Archaeologists almost always define types via attribute lists, sometimes prescribed, sometimes polythetic. But the mind does not construct categories this way. The handaxe itself is an excellent example. Many Paleolithic specialists have constructed their personal category of “handaxe” through repeated exposure, not through a set of attribute prescriptions. It is a prototype based on exemplars. When pressed to define the “type,” they struggle to compile a list of attributes. For example, Corbey and colleagues (Corbey, Jagich, Vaesen, & Collard, 2016) provide an attribute list: “Acheulean handaxes were produced by the bifacial reduction of a block or large flake blank around a single long axis. They have a cutting edge in the secant plane, and range in shape from lanceolate through ovate to orbiculate” (p. 6). The problem is that this definition misses something essential about the Acheulean handaxe, and in fact the definition is so broad that it applies to artifacts from all over the world from almost all time periods, many of which specialists would not consider to be true handaxes (Wynn & Gowlett, 2018). Isaac (1976) actually came closer to describing the nature of artifact categories when he emphasized a metaphorical design space.

Gowlett’s *design imperatives* are similarly an excellent example of prototype, but one whose design space was primarily ergonomic. All of the design imperatives consist of bundles of ergonomic and visuospatial features.

1) The glob-butt consists of muscular tensions and resistances tied to heft (perceived weight) and grip security. It is a tactile motor package.
2) Forward extension is also an ergonomic bundle based in the musculoskeletal feel of leverage, and the duration and resistance of a cutting stroke. Here there is also a set of neural visuospatial correlates associating the tactile elements with the length dimension of the artifact.

3) Edge support combines musculoskeletal resistance with assessment of task efficiency and experience of breakage. Here, too, there are visuospatial features, including edge angle.
4) Lateral support is primarily a musculoskeletal bundle linked to grip resistance and security, with visuospatial correlates.
5) Thickness control acts as a counter to heft and fatigue. Heft correlates with size, but because length and breadth have other ergonomic constraints, the only size dimension free to reduce heft is thickness. Thickness control presumes that forward and lateral extension are primary ergonomic concerns.
6) The musculoskeletal aspects of heft and grip are asymmetrical in relation to artifact form, and the optimal biomechanical solution is for heft to be biased toward the location of grip. The result is skewness.

Each of these ergonomic bundles assembled via the cognitive mechanisms of attention and association. Hominin butchers, for example, noticed (attention) the feel of a core tool with a longer cutting edge, associating its heft and stroke length with visuospatial features of the tool (forward and lateral extension). Eventually all six of these ergonomic bundles coalesced into an artefactual prototype—a biface—and, more significantly, hominins came to internally execute and simulate the bundle. The first true tool type had emerged. It was in a very real sense a visuospatial, ergonomic category, an embodied and extended concept. The hominins came to an awareness of this prototype as an ontological thing that they could think about. We know this because they soon added a non-ergonomic feature to the mix: visual pleasure.

Consider now the artifact in **Fig. 2b** from the site of FLK West in Olduvai Gorge (Diez-Martín et al., 2015). This handaxe differs in several respects from the slightly older Kokiselei example (**Fig. 2a**): First, the blank is a large flake, not a cobble; second, at over 30 cm in length, it is very large for a biface, or indeed any hand-held tool; and third, it is bilaterally symmetrical. Each of these three features suggests that the maker had thought about the tool itself, not just about a task to complete. The resulting handaxe is arguably too large to have been a hand tool. It also dwarfs the other FLK West handaxes (Diez-Martín et al., 2015). There is no obvious mechanical reason for this tool; a smaller handaxe, like others from the site, would have been much easier to wield. It may have had a role in social display of some sort (Cole, 2014; Shipton, 2010), perhaps as simple as showing off. However we come to understand it, the exceptional size of this handaxe suggests that the tool itself was the goal. Gigantism became a kind of recurring motif for Acheulean knappers, with giant examples occurring in most areas with large enough clasts. There good examples from throughout the African Acheulean (Berlant & Wynn, 2018), but also from Europe, where large clasts are rarer (e.g., Cuxton [Wenban-Smith, 2004]; also see **Fig. 3**).

The spatio-temporal organization of biface technology corroborates the knappers' reliance on a tool concept. The Large Flake Acheulean (Sharon, 2008, 2009) provides the best documented examples. Large flake manufacture is the first step in a two-step procedure to produce a biface(Sharon, 2009). By convention and as the term is used here, large means over ten centimeters in maximum dimension. Producing a flake of this size required that the tool maker use a large core that was probably too heavy to be carried very far. Their immediate goal at the source must not have been task performance, but tool production, or at least blank production. The flake for the FLK West handaxe was over 30 centimeters in length, a very large flake that required an over-the-head, two-handed hammer strike on a boulder-sized core (Jones, 1981). Knappers initially produced flake

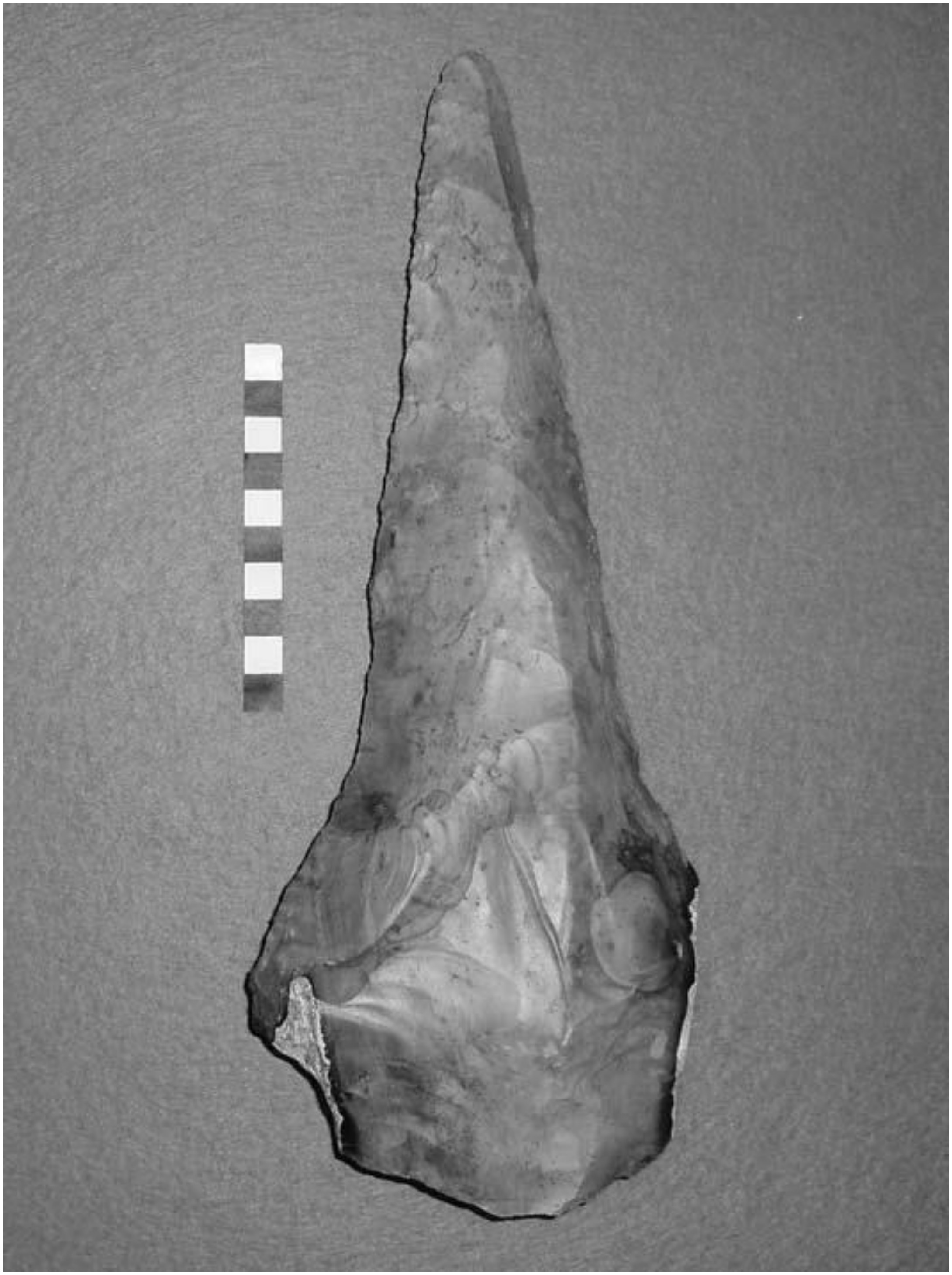


Figure 3. Giant ficron handaxe from Cuxton, England; stratigraphic age estimated as late as MIS 8 (*ca*. 300,000 years ago) (Wenban-Smith, 2004). Photograph by Thomas Wynn.

blanks at the raw material source, carried the blanks to a second location where they trimmed them into finished artifacts, and then sometimes carried them again to another location. Gallotti and Mussi

(2017) refer to such technical sequences as being “fragmented” and have documented their presence as early 1.0 Ma in Ethiopia. Archaeologists have described similar fragmented technical sequences for many Acheulean sites and localities (Barkai, Gopher, & LaPorta, 2006; Goren-Inbar & Sharon, 2006; Hallos, 2005; Paddayya, Jhaldiyal, & Petraglia, 2006; Roberts & Parfitt, 1999; Sampson, 2006). At Gesher Benot Ya’aqov 780,000 years ago, knappers used different blank production procedures at the quarry for handaxes and cleavers, indicating that they anticipated completing particular varieties at a subsequent time and place (Herzlinger, Wynn, & Goren-Inbar, 2017). They initiated two different fragmented sequences that had different final artifact forms as goals. They clearly thought about the tools themselves, not just about a specific task to complete. Their immediate goal at the source must not have been task performance, but tool production, or at least blank production.

The bilateral symmetry of this handaxe is an overdetermined quality. That is, bilateral symmetry added nothing to the functional potential of the large flake, yet its maker invested the effort to impose it (there is a long history of attempts to demonstrate an advantage to particular handaxe shapes, but none has been successful; Key & Lycett, 2017; Machin, Hosfield, & Mithen, 2007). The simplest way to account for this overdetermination is through the pleasure the maker experienced in producing a symmetrical shape, an effect referred to as *visual resonance* (Hodgson, 2000, 2009, 2011, 2015). Cells in the primate visual cortex evolved to be sensitive to bilateral symmetry (symmetrical things are almost always living organisms), and arousal of these cell groups also elicits arousal of opioid releasing cells in the pleasure centers of the brain. Simply, symmetrical patterns are more pleasing to the eye than non-symmetrical patterns. Crucially, there is no need to posit a mental image: Visual resonance would draw a tool maker to produce a symmetrical shape if possible, but *only if the knapper attended to features of the tool itself*. Attending to material features is essential to literacy as well, suggesting an inherent continuity between stone tools (whose interaction actualized the ability to form and manipulate concepts mentally, as if they were physical objects) and writing (whose interaction actualized the ability to form and manipulate concepts physically, as if they were mental objects).

The large size and bilateral symmetry of the FLK West handaxe were qualities that enhanced the basic ergonomic imperatives of biface manufacture instantiated in the handaxe from Kokiselei. Bilateral symmetry is not itself an ergonomic feature; indeed, the design imperative of skewness would bias a tool maker toward a slight asymmetry. If, as seems plausible, large size played a role in display of some sort, then size, too, had become a non-ergonomic feature linked to visual impact. The tool maker must have been *thinking about* the visual appearance of the tool itself, not just a task to be completed. These extra-ergonomic features are interesting in their own right, but for the purpose of this essay, they serve to confirm that a coherent set of features had coalesced into a stable tool concept available for thought. Hominins had started to think about the materiality they used, and in doing so likely recruited the same kinds of neural muscles seen today as activity in mirror neurons and the cerebellum, during handwriting and mathematics, etc.

Neural Muscles: Into the Future

The seemingly simple technological/cognitive development of the biface would have immense significance for hominin evolution. It situated hominin technology well beyond anything known for apes and monkeys, and was the seed for the progressive, conscious manipulation of technology that both characterizes and differentiates the human species, though fruition of this trend would be another long time coming. However, our ancestors did not start *thinking about* materiality one day as a miraculous discovery (nor, for that matter, can it be implausibly ascribed to alien contact). Instead, *thinking about* materiality was the consequence of several million years of anthropoids making and using tools, and at least a million years of patient stone knapping by hominins. For example, when hominins began to carry cores and flakes from place to place, one cognitive consequence was a temporal extension of the hominins' contact with this materiality, a likely prerequisite for a permanent, stable, tool concept. In these ancestral species, *thinking through* the materiality of stone tools ultimately gave us the ability to *think about* them as concepts. In more recent peoples, *thinking through* the materiality of making marks on things like clay, papyrus, and bone opened up a new way of *thinking about* concepts, through a material form that allows ideas to be subjected to analysis, reflection, revision, and refinement, and transmitted through space and time to preserve, educate, and provoke (Olson, 1994).

In developing neural muscles that interact with material forms, our ancestors became the species that can both *think about* and *think through* materiality, and both continue to change us. Over the course of our evolutionary history, these muscles (to continue the metaphor) have become stronger and change more quickly in response to interactions with material forms. Certainly, when biface manufacture is contrasted with writing, what particularly stands out is that the neurological changes involved in the latter required a much shorter span of time than those of the former. What might this suggest for an evolutionary history that continues to unfold? For example, as we increase our use of collaborative media like the Internet and Twitter and tools like smart phones and computers, and decrease behaviors like handwriting, our brains are changing (Sülzenbrück et al., 2011). We already see change in conceptions of privacy (though the implications and future consequences of this are far from clear), and we can speculate about effects on memory. However, our brains will also change in ways we cannot foresee, since we may have little idea of what might emerge next. Further, we are unlikely to see the changes taking place, since the temporalities over which they emerge are multigenerational and longer.

We may simply remain content with noticing at some point that the brain has started to do something new, as the Mesopotamians once did when writing began to speak to them, a phenomenon so astonishing that many cultures have ascribed it to divine intervention (Senner, 1989). But as the species that both *thinks about* and *thinks through* materiality, we might also consider asking questions along the lines of these: Is the trend toward faster change continuing, or has it slowed or reached some sort of plateau? Can we become aware of cultural/evolutionary changes in brain function as they are taking place? Can we gain any sense of their direction or even control over the process, either deciding whether it is a direction we want to follow or changing its speed of progression? Would we be able to master the process whereby material forms become more effective and efficient in shaping our behaviors and brains? Has material engagement elicited the full range and capacity of human cognition, or is there currently untapped potential for conceptual systems as significant as those realized through stone tools and writing? To what extent does materiality influence cognition (i.e., analogous to the more recent versions of the principle of linguistic relativity) or perhaps even limit our cognitive potential? And what sort of methods and theories will we need to develop in order to investigate functional and structural change in brains over cultural and evolutionary time spans?

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