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Abstract

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Human cognitive evolution is an aspect of human origins research that can be better understood through the experimental replication of the technologies of long-dead human ancestors. Changes in the mechanisms that are part of social learning and the evolution of proto-language have been advocated as prerequisites for cultural accumulation and technological development, specifically with regard to the leap from Oldowan flaking technology to the creation of the first Acheulean bifaces. In this study, a novice knapper attempted to learn how to produce hand-axes under learning conditions without major social input and verbal interactions with more experienced knappers in order to evaluate whether or not it was possible for an inexperienced individual to learn how to make a hand axe under such conditions. From the hand-axes and debitage produced by the neophyte during the experiment, a selection of skill indicators (such as shape and size variables) has been evaluated for potential use in analyses in a larger follow-up study. Over the course of the 40-hour learning period, there was very little significant change in the objects produced by the subject. The main significant changes were related to attributes of the platform, showing that there was experimentation with different combinations of force application, angle of blow, and hammerstone selection. The main hypothesis generated as a result of this study is that learning bereft of a physically present teacher and linguistic input is to some degree restricted or delayed. This hypothesis, if supported by the results of future experiments, could help elucidate the evolution of the cognitive mechanisms of social learning and language in the Paleolithic, especially since these cognitive mechanisms are involved in the production of ancient stone technologies evidenced by the archaeological record; more specifically, this research could provide insights into the Oldowan-Acheulean transition and the temporal and geographic variation within the Acheulean.

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Introduction

Understanding the cognition of our hominin ancestors is one of the key questions of anthropology and is of particular significance in human origins research. In order to develop a model of cognitive evolution, scientists have sought answers from a number of sources, from comparing human and primate brains and cognition to examining the skulls and endocasts of ancient hominins (Gibson, 2002; Roth and Dicke, 2005; Holloway et al., 2009). Of particular interest here is the archaeological remains left by the forbearers of humankind: stone tools are one of the key lines of evidence that help us understand the minds of pre-modern humans. The Acheulean hand-axe, a bifacial, teardrop-shaped stone tool from approximately 1.7 million to 250 thousand years ago, stands out as one of the more iconic representatives of prehistoric artefacts and serves as the focus of this study (Toth and Schick, 2007). Experimental replication of ancient technologies, like the hand-axe, provides anthropologists with a way to ñget insideò the minds of the long-dead tool-makers. Social learning, a suite of cognitive mechanisms, and language (as well as the interplay between the two) have been implicated with cultural complexity and ómeteoricô rise in technological sophistication achieved by humans and by humans alone (Montagu, 1976; Reynolds, 1994; Castro and Toro, 2004; Goren-Inbar, 2011; Sterelny, 2011); these are also cognitive capabilities that could be examined through the lens of experimental archaeology.

By recording the learning process as a novice hones their skill as a knapper, this study aims to lay groundwork for further research into learning in the Paleolithic, especially by generating hypotheses about Acheulean hand-axe skill acquisition. The lithic measurements evaluated in the study could potentially be useful as indicators of skill development. These indices would be applied in larger scale research to examine the relationship between variable conditions (such as language absence and presence, or ósocialô and óasocialô learning conditions) and adopting the hand-axe making skill, which would then provide a better understanding of the cognition of our ancestors. In particular, it is my hope that this and future research will build upon previous discourse and experiments related to the relationship between technology and language, especially the role language may have played in the propagation of technological advancements. More specifically, this study aims to determine whether it is possible for an individual to learn how to make a hand-axe without major social or linguistic (verbal or gestural) input (which could be interpreted as promoting emulative/imitative learning within conditions that may be considered as being characterized by niche construction), as well as tracing this process through various quantifiable markers and cognitive events (as recorded in a subjective journal).

Background

Overview of the Paleolithic

The era of technology from 2.6 million years ago (Mya) to approximately 250,000 years ago is known as the Early Paleolithic and is divided between two industrial complexes: the Oldowan and the Acheulean (Toth and Schick, 2007). Stone artefacts from Gona, Ethiopia, dated at approximately 2.6 to 2.5 Mya, represent the oldest direct evidence of stone tool manufacture and use and mark the beginning of the Oldowan industrial complex (Semaw et al., 1997). The Oldowan faded from existence approximately 1 Mya. The Acheulean industrial complex emerged around 1.75 Mya and persisted until 250,000 years ago and spanned geographically across Africa, Europe and Asia (Beyene et al., 2013). The Acheulean represented an increase in technological complexity and involved the shaping of the core to produce a tool rather than focusing on the detachment of flakes (a piece of rock removed via striking the core with a hammer) to be used as tools. The modifications involved in Acheulean tool making produced objects such as óbifacesô like a hand-axe.

The progression of technology from the Oldowan to the Late Acheulean coincided with increasing brain capacity and increasing encephalization (increasing brain size in relation to expected brain size for an animal of equal body size) (Stout et al., 2008; Holloway et al., 2009). Technological change also coincided with spatial reorganization of the hominin brain (based on endocasts of extinct hominins), including reorganization of the frontal lobe (specifically with respect to third inferior frontal convolution, changes in the Brocaôs area, and widening of the prefrontal cortex) and the emergence of brain asymmetries (left occipital and right frontal petalias) (reviewed in Holloway et al., 2009). The increases in brain size as well as the changes in how the brain is organized were likely associated with increased complexity of the cognitive abilities of these hominins (asymmetry of the brain as well as changes in the Brocaôs area being heavily associated with language, for example), which may explain the emergence of bifacial flaking technologies that would persist for over one million years and which have yet to be replicated under experimental conditions by modern great apes. Under experimental conditions, captive chimpanzees have learned to perform Oldowan-like flaking (Toth and Schick, 2009), which suggests that the social learning mechanisms necessary for Oldowan technologies is shared between humans and apes, but the mechanisms which allow for progressively more complex technologies like Acheulean hand-axes would require a mechanism either not present or not fully elaborated in chimpanzees and other non-human primates.

Review of Social Learning

Because the focus of this study is the social learning processes involved the acquisition of the Acheulean hand-axe making skill, it is necessary to define both social learning and some of the frequently mentioned modes of learning that are classified as being within the social learning spectrum. Social learning is learning achieved through either interacting with another animal or by observing another individual performing an action (Heyes, 1994). Social learning is sometimes referred to as ñsocially-biased learningò, in that social, environmental factors affect the transmission of a behavioral practice from one individual to another in ways that cannot be achieved through learning in a purely asocial context (Fragaszy, 2003). Among researchers in the fields of psychology and cognitive science, there exists a degree of ambiguity and discrepancy with regard to how key processes in social learning are defined (Whiten et al., 2009). For the sake of congruency, the forms of social learning discussed in this review will be defined as follows:

1. In stimulus enhancement, a subject is attracted to a particular object or stimulus, because it has observed another animal (usually a conspecific) interacting with the stimulus (Heyes, 1994).
2. In imitation learning, a subject copies the motor patterns or components of an action or behavior being performed by another agent (conspecific or otherwise) (Whiten et al., 2009).
3. In emulation learning, a subject attempts to replicate the change in the environment produced by the action of the individual being observed. Emulation learning can be further differentiated into smaller categories, but a simpler definition will be maintained here (Whiten et al., 2009).

4. In teaching, another individual adjusts its behavior in order to facilitate the learning process of another individual (Thornton and Raihani, 2008).
5. Progressive teaching or scaffolding is teaching that adjusts as the pupilôs level of ability increases over time (Thornton and Raihani, 2008). The ability to teach via scaffolding requires an understanding of what other individuals know (ótheory of mindô). Progressive teaching is also linked to cultural óknow-howô and, in the case of humans, benefits largely from social environments embedded with cultural resources.
6. The term apprenticeship is limited only to teaching systems that have become institutionalized or in cases where efficient evidence of apprenticeship systems exist.
7. Niche construction is alteration of the external environment by an organism. In relation to social learning, niche construction involves the accumulation of artefacts and objects that promoting learning within the home environment of a population (Fragaszy et al., 2013).

In order to better understand this particular set of cognitive mechanisms, researchers have analyzed evidence from living non-human primates, living humans, paleontological and archaeological remains, and experimental work, which has combined elements of the other three categories.

Social Learning and Tool Use in Non-Human Primates

Whether viewed from the perspective that humans are qualitatively unique among the primates with forms of cognition not achieved by our closest relatives or from the perspective that humans possess refined versions of shared primate cognitive mechanisms (achieved through quantitative changes such as growth of information processing regions in the brain), primate research is important to developing models of human cognitive evolution and technological accumulation (Vaesen, 2012; Roth and Dicke, 2005). Of particular interest to this study, Rossano proposes that there is evidence of skill acquisition and the practice necessary to develop expertise in non-human primates and in the archaeological record (2003). Teleki has gone even further to propose that technical skills such as subsistence technology are ñfirmly rooted in [primate] prehistoryò, suggesting that the beginnings of the advanced cognition behind tool use predate the phylogenetic split between humans and non-human primates (1974).

There is extensive evidence that non-human primates engage in emulation learning, in which an individual attempts to replicate the ñchange of state in the worldò achieved by the individual being observed (Tomasello and Call, 1997), as opposed to only stimulus enhancement in which an individual is attracted to an object being manipulated by a conspecific (Roth and Dicke, 2005). Under experimental conditions, researchers have demonstrated that captive primates can acquire tool use skills through an emulation-learning mode when causal relations are obvious, but may also partake in simple imitation when causal relations are not so clear (Nagell et al., 1993; Horner and Whiten, 2005). On the contrary, human children replicated the task exactly as performed by the demonstrator. Evidence of cultural transmission of tool using behaviors through emulation has also been observed among wild chimpanzees (Biro et al., 2003). Wild chimpanzees almost exclusively observed the behaviors of individuals in their own age group or older, suggesting that there is an awareness of a relationship between age and level of expertise. óGhostô experiments in which the agent performing an action is seemingly absent (there are not perceivable body movements observable by the subject) have been conducted to further investigate the social context of learning. Chimpanzees are able to successfully learn how to accomplish simpler tasks, but in the case of more complex tasks, chimpanzees are unable to learn to perform an action when there is no conspecific or even human teacher within the visual field (reviewed in Whiten, Schick and Toth, 2009), reinforcing the idea that learning complex skill hierarchies benefits from a social context.

Evidence of imitation also comes from species more phylogenetically distant from humans. Under experimental conditions, marmosets would imitate the means of extracting a mealworm from a container (Voelkl and Huber, 2000); if the demonstrator opened the container with their mouth, the marmosets would open it with their mouth, and if the demonstrator opened the container with their hands, the marmosets would open it with their hands. Although this example of imitation is applied to a relatively simple task, it may suggest that the evolutionary origins of imitative learning lie much deeper in the past. This also suggests that imitation, as a more basal characteristic of primates, may not be the form of social learning, which is responsible for human levels of technological and cultural proliferation. However, as a caveat, the potential for evolutionary convergence (as opposed to characteristics that derive from shared ancestry) among humans and non-human animals is a potential confound preventing us from drawing hasty conclusions about the evolution of cognitive traits like social learning.

The phenomenon of tool use has been observed in several species of non-human primates (though mostly restricted to great apes) (van Schaik, Deaner and Merrill, 1999). Examples of this include the use of tools in extracting and preparing food sources by capuchins (Chevalier-Skolnikoff, 1990, Fernandes, 1991), macaques (Beck, 1976), orangutans (Galdikas, 1982), gorillas (Breuer, Ndoundou-Hockemba and Fishlock, 2005), and chimpanzees (McGrew, 1974; Biro et al., 2003; Pruetz and Bertolani, 2007). According to van Schaik and Pradhan (2003), the likelihood of an individual acquiring a tool use skill, is dictated by the probability of three factors: innovation, social learning, and sociability. Complex skills like tool use appear most frequently in highly sociable primates with advanced levels of innovation and of social learning, which allows for the production and cultural transmission of such skills. Solitary and semi-solitary animals are less likely to develop skills such as tool use, because less gregarious or sociable animals would be less likely to benefit from social learning. According to van Schaik and Pradhan, the availability of experts and social tolerance are prerequisite for social learning and the development of complex skill hierarchies (2003). Jaeggi and colleagues have observed the vertical transmission of foraging skills from mothers to offspring via observational learning among orangutans (a relatively asocial great ape) (2010). These observations confirm the supposition of van Schaik and Pradhan (2003), but also show that the scale of the transmission scheme (mother-child vertical transmission) restricts the levels of cultural accumulation.

In stark contrast to the wealth of evidence of social or observational learning in non-human primates, there is scant evidence of teaching or direct instruction among mankindõs phylogenetic cousins (reviewed in Thornton and Raihani, 2008). Castro and Toro theorized that the lack of more guided instruction among primates (approval and disapproval of offspring behavior by adults) may be responsible for the disparity between non-human primates and humans in relation to cultural accumulation, especially the accumulation of culturally defined (instead of instinctual) traits like tool use and tool manufacture (2004); primate imitation is enough for the transmission of culture, but it has only a limited contribution to the development of the ñcumulative inheritance systemò found in *Homo sapiens* but not in apes and other non-human primate species. Evidence of progressive teaching in the animal kingdom comes largely from Carnivorans like cheetahs and meerkats (Caro and Hauser, 1992; Thornton and McAuliffe, 2006). Cheetah and meerkat mothers release prey animals to facilitate the learning process of their young and will adjust this behavior based upon the age of the offspring. Progressive teaching among non-human animals differs from that of humans in that most of the skills being taught seem to be óbiologically prespecifiedô, otherwise rooted in genetic predispositions (Thornton and Raihani, 2008). The teaching process functions as a way to quickly promote the development of skills, such as prey capture techniques, that are already largely ingrained in the biology of the ópupilô animal; in humans, progressive teaching enhances the development of skill hierarchies that would not exist without social input.

Recent evidence from Fragaszy and colleagues suggests that the direct presence of a conspecific modeling a skill-based action is not the only requirement for the acquisition of tool use skills (2013). Based on observations of wild capuchin monkeys and chimpanzees, the authors posit that the availability of artefacts, such as tools previously used by conspecifics, facilitates the learning process, and the inheritance of artefacts aids in the cultural transmission and accumulation in both non-human primates and humans. Positing a positive correlation between the density of cultural artefacts present in a community and the rate of cultural transmission or accumulation may account for the differences in cultural and technological complexity among humans and their relatives. Scaffolding among humans can also be differentiated from teaching in non-humans because of the social context: the learning process occurs within social environments with plenty of available cultural knowledge resources and opportunities for individual practice, or minimally time for interaction with the resources. Niche construction may not be unique to humans, but the degree of artefact and knowledge resource density found in humans and our recent predecessors is unmatched by any other species. This disparity in the degree of complexity of niche construction may constitute the sort of quantitative difference highlighted by continuity model adherents (Roth and Dicke, 2005).

Social Learning and Skill in Contemporary *Homo sapiens*

Psychology of learning and skill

As previously discussed, non-human primates have a large repertoire of social learning mechanisms related to the acquisition of skills, including emulative, imitative, and limited teaching capabilities. The question remains as to what mechanisms are responsible for the differences in terms of technological and cultural complexity found in humans and non-humans. Csibra and Gergely state that social learning and communication exist as properties of many animal species, but the overlap between the two is very rare (2011). Humans possess what they term as ñnatural pedagogyò, a form of learning facilitated by communication, which may otherwise be described as teaching of cultural knowledge via communicative media (verbal and gestural instruction).

Much of the research into the processes of social learning in contemporary humans comes from childhood development studies, with a focus on imitation learning. Regardless of whether young children observe a task in which causal reactions are apparent or obscured, they copy the behavior with ñhigh fidelityò (reviewed in Whiten et al., 2009). Children at age 5 are more likely to óblindlyô imitate an action than children at age 3, contrary to the initial assumption that such imitation of an action would cease as the cognition of individuals matures. Researchers have also demonstrated that children will continue to over-imitate even when informed that particular actions in a sequence are unnecessary to completing a task. Over-imitation might also allow for the transmission of actions that are more arbitrary and which may be of a more semiotic nature (such as those involved in language).

Recent experiments by Muthukrishna and colleagues (2014) seem to confirm the role of sociality in learning, similar to how the size of social groups and therefore the availability of expert models promotes social learning in non-human primates (van Schaik and Pradhan, 2003). The work of Muthukrishna and his co-authors highlights the role of a learnerôs social context in the fidelity of transmission of skills, providing a template for understanding skill learning and cultural transmission in both a naturalistic and ethnographic context.

Ethnography

Ethnographic accounts of tool-making and crafts provide evidence of this unique (among living species) form of social learning. For example, traditional textile-making techniques among pastoralist tribes in Iran and Central Asia are transmitted from mother to daughter using an progressive teaching system in which the manner of teaching by the mother adjusts to the skill level of the daughter (with little linguistic exchange) (reviewed in Tehrani and Riede, 2008). Further evidence of progressive teaching or scaffolding comes from a cross-cultural survey of traditional hunting societies (MacDonald, 2007). Children learn to construct weapons or traps by observing adults and a great amount of practice, both using or playing with the pre-existing tools and independently producing their own tools. Children typically learn to use and make tools from their fathers or from other male relatives; individuals who were experts at certain skills were typically sought after as teachers. Generally, verbal instruction plays a very minimal role in the development of a tool manufacturing skill among these hunters. Research on the Aka and Boki foragers of the Congo Basin conforms to the notion that pedagogy is rarer than observational forms of learning among hunter-gatherers (and confined mainly to vertical transmission of knowledge from parents to their infants), but might suggest that teaching is important in the transmission of cultural knowledge, such as foundational schemata (Hewlett et al., 2011).

In his study of the adze makers from Irian Jaya, Stout observed a learning process that involved scaffolding (2002). Langda adze makers undergo a period of apprenticeship in which they procure the skills necessary for stone tool-making; apprentice learners benefit from observing practiced flint knappers and practicing with resources allotted to them (which are limited). Apprentice learners also receive verbal instruction and active assistance from other knappers. Advice and instruction in stone knapping come from the community of stone knappers as opposed to only a single teacher (Stout, 2005). Apprentices benefit from having a social environment enriched with available teaching resources and learning opportunities not limited solely to observation and independent practice. The apprenticeship period required for the mastery of stone tool production techniques generally lasts several years: five or more years among the adze makers of Irian Jaya (Stout, 2002). Further contemporary ethnographic accounts of stone tool-making, and more specifically the learning processes behind stone tool-making, are very limited due to the constantly dwindling practice of such traditions (Stout, 2002).

Filling in the gaps: social learning and skill acquisition in extinct hominins

Evidence of social learning in fossils and ancient artefacts

Based on comparisons between studies of living primates and living humans, researchers infer that ancient hominins would have possessed a ñpsychological toolkitò that enabled the learning of complex skills through social learning (Whiten, Schick and Toth, 2009). Part of developing an understanding of the social learning abilities of ancient hominins is to make inferences about their cognition by looking at evidence in the archaeological record.

Sterelny argues that the emergence of behavioral modernity among *Homo sapiens* is a result of a niche construction model of cultural accumulation (2011). Sterelny believes that one of the hallmarks of modern human behavior is the creation of social environments that allow for learning, particularly apprentice learning. Increases in the concentration of information and cultural knowledge embedded in the human social environment (potentially due to demographic changes) allows for the greater complexity of artefacts found after the beginning of behavioral modernity 50,000 years ago; this level of complexity cannot be achieved solely through imitation learning, but depends on the availability of artefacts or symbols in the environment to facilitate the acquisition of knowledge and motor skills. However, according to Sterelny, guided instruction is not necessary to the acquisition of skills, such as tool use and tool making.

Based on cultural differences between local communities of hominins, Wynn and colleagues concluded that the Oldowan industrial complex was compatible with the social learning capacities possessed currently by living great apes and would not have necessitated the level of social learning complexity found in modern humans (2011). The occurrence of distinct regional variations in the Acheulean reduction process, however, has alternatively been proposed to indicate that ancient hominin stone tool manufacturing depended on imitation learning in order to be transmitted culturally (Shipton, 2010). Combining the evidence of local stone tool cultures among hominins with endocasts from the early *Homo* cranium KNM-ER 1470, which have a Brocaȏs region that resembles modern *Homo sapiens* as opposed to living great apes, Shipton identified an approximate date of 2 Mya for the concurrent emergence of a more *sapiens* mirror neuron system (a system of brain regions, which activate both in response to observation of an action and performance of the same action) and human-like imitation learning. Evidence from early Paleolithic sites has largely been argued to be representative of imitation learning as opposed to representative of mechanisms like progressive teaching. The majority of evidence for progressive teaching, apprenticeship-like teaching in particular, comes from much later than the Acheulean in the Late Paleolithic (Pigeot, 1990, reviewed in Tehrani and Riede, 2008). The gap in time leaves the origins of human-like teaching behaviors an open-ended question (as far as when, where, why, and how human-like teaching emerged), possibly emerging as soon as the Acheulean, but with concrete evidence hard to come by.

Experimental replication of ancient industrial complexes

Experimental reproduction of ancient stone tool industries is one of the approaches that researchers in the field of Paleolithic archaeology have adopted in order to develop a better understanding of the mind and behaviors of extinct hominins (Schick and Toth, 1994). In more recent times, experimental archaeology has been combined with primatology and neuroscience in order to develop a more holistic understanding of the cognitive processes, like social learning, that underlie the production of tools like hand-axes (Toth and Schick, 2009; Stout and Chaminade, 2011).

R.V.S. Wright conducted the first experiment in which the capability of a living primate to produce stone tools was examined (1972). In Wrightôs study, an orangutan successfully learned through an observational learning scheme to remove flakes from a core (to a limited degree). In a later experiment, bonobos were taught to replicate the Oldowan technique of flake production and stone tool use (Toth and Schick, 2009). The bonobos learned to imitate the procedure, but, unlike humans, were unable to attain the level of skill found in the archaeological record or achieved by modern human flint knappers, even over the course of several years (at the time of the study, the bonobo Kanzi flaked stone for 18 years); the skill level of extinct hominins was intermediate between the experimentally replicated tools produced by bonobos and by human flint-knappers. Bonobo-produced cores were heavier and less heavily reduced with fewer scars and more battering. It is worth note that wild bonobos and chimpanzees have not been observed flaking stones (Whiten, Schick and Toth, 2009). Furthermore, the bonobos in the study initially obtained the Oldowan flaking technique through observing humans and not from a conspecific or through innovation (if it has arisen independently, the mechanisms for faithful transmission possessed by bonobos or proto-bonobos may have been insufficient for maintenance of such a skill over the span of many generations).

Based on a comparison of Acheulean hand-axes from the Middle Pleistocene of Boxgrove, UK with hand-axes produced by modern humans of varying skill, Stout and fellow researchers discovered that the prepared platform flakes produced by ancient hominins from Boxgrove were most similar to those flakes produced by modern human knappers (2014). Based on these similarities, they concluded that mastery of the platform preparation technique characteristic of this prehistoric population would have required social learning capacities beyond just observation and verbal or gestural instruction: capacities along the lines of more advanced progressive teaching or forms of niche construction similar to those previously mentioned in both an ethnographic and archaeological context. At the same time, platform preparation would not have necessitated the level of social learning abilities possessed by modern humans.

Hecht and colleagues have demonstrated that the acquisition of Paleolithic stone tool making skills elicits structural remodeling of inferior frontoparietal regions of the brain (2014). This conclusion is based on imaging studies of modern human brains, which are significantly larger than the brains of the hominins that made Acheulean hand-axes, for example. The changes to the brain experienced by these ancient hominins, due to their smaller brains, would have been similar if not proportionally greater than the changes experienced by modern humans. Neuroplasticity as a trait of the hominin nervous system would have been a fundamental aspect of the ability of ancient hominins to learn and acquire complex skills like stone tool production.

Tool use and language: complementary or coincidental?

The relationship between the evolution of tool use and technological cultures and the evolution of language has been explored by researchers as far back as Darwinôs own treatise on human evolution (1871). The link between tool use and language has been characterized in a few different ways. Some researchers have suggested that language would have aided in the transmission of tool-making knowledge and the propagation of tool use cultures (Montagu, 1976; Reynolds, 1994). Goren-Inbar states that verbal communication, in addition to nonverbal forms of observational learning, would have been necessary for the production of the degree of consistency found within local traditions of Late Acheulean bifaces (2011), which would be in line with the observation of the involvement of verbal and gestural communication in the transmission of stone flaking skills in Irian Jaya (Stout, 2002), but not quite as compatible with the lack of evidence for pedagogical transfer of knowledge in the tool making skills of traditional hunters (MacDonald, 2007). Others have proposed that the relationship between language and tool use is more intricate: the developments in the two behavioral traits were a result of co-evolution. As an example, artefacts from as early as 1.9 million years ago demonstrate that ancient hominins had preferential right-handedness (Toth, 1985). The brain asymmetry correlated with handedness is considered by some to be a precursor to the neurological changes for asymmetries necessary for the development of spoken language (Dibble, 1989). Recent discoveries in neuroscience have contributed to this model of language-tool use coevolution by showing that certain neural circuits and pathways are involved in both tool-making and language, which would both constitute forms of complex, goal-oriented action (Stout et al., 2008; Stout and Chaminade, 2011). Of particular interest to the field of social and observational learning, similar activation of the cortex of the inferior parietal lobe suggest that the integration of stimuli necessary for the imitative processes of social learning is involved in the transmission of both language and tool use. These lines of evidence point at a model of human evolution in which the capabilities for stone tool making and language are intricately linked whether that may be a pedagogical basis (teaching through verbal and gestural communication) or a coevolutionary basis evidenced by interrelated neural networking.

On the other hand, the mechanisms behind both human language and human tool use may only be derivatives of the same pre-human cognitive foundations, and therefore not so explicitly inextricably linked. Contrary to the body of evidence that supports the coevolutionary model of language and tool use, other studies have shown that verbal communication may not have been necessary for cultural transmission of tool-making. Proponents of a non-linguistic model of stone tool use contest the notion that the production artefacts like hand-axes necessitates spoken language with grammar and symbols (Wynn, 1995); tool-making remains, however, ñmimeticò (i.e., produced by imitative or emulative processes). In one study, previously untrained human flint-knappers were separated into two experimental groups: the first group was given verbal instruction, and the second group was trained without spoken language (Putt, Woods and Franciscus, 2014). The results of the study showed no major quantitative or qualitative differences between the bifaces produced by the two groups. Thus, spoken language provided no advantage in the transmission of flint-knapping knowledge in this particular study. The verbal instruction group was subject to over-imitation of the actions of their teachers, suggesting that verbal instruction may even have negative consequences in learning to make stone tools.

In a similar vein, Morgan and colleagues investigated the fidelity of transmission of the Oldowan tool-making skill across five different social learning mechanisms: reverse engineering, imitation/emulation, basic teaching, gestural teaching and verbal teaching (2015). Greatest improvement in total flake quality emerged in chains where gestural or verbal teaching was the mode of transmission. Emulation/imitation provided only limited improvements over reverse engineering. From these results, the authors concluded that low-fidelity social transmission (imitation or emulation) may have been responsible for the ñ~700,000 year stasis of the Oldowan technocomplexò and that the jump in technological complexity from the Oldowan to the Acheulean may be explained by the development of (at least limited) teaching and linguistic capabilities. However, the relative short duration of the learning/teaching period (5 minutes) and the test phase (20 minutes) are not ideal for the mastery and transmission of such a technique. Also, because the experimental design did not include an examination of social transmission for Acheulean hand-axe production, it is difficult to draw conclusions about the differences between the two industries, especially in terms of cognitive differences between the hominins involved.

The relatively small scope, limited to non-existent replication of results, and differing results and conclusions across studies does not resolve what is still an ongoing debate about language and technology; a better understanding of the role of verbal and gestural instruction in the acquisition of tool manufacturing skills (and, in broader terms, human social learning) requires further investigation by archaeologists. Importantly, there is a general lack of an estimate for the amount of time necessary to learn how to make a hand-axe in the literature; the assumption is that five hours is not enough, so this study has extended the learning period to forty hours, which is at least much longer than previous studies (if not extensive enough to cover the entire learning process). This pilot study thus aims to build upon this research by producing hypotheses that may prove beneficial for future research.

The main research question in this study is straight-forward: can an inexperienced individual learn the knapping techniques necessary for the production of an Acheulean hand-axe without receiving guided instruction and, more specifically, verbal and gestural input? Are emulative/imitative learning, independent practice, and access to cultural resources enough for this particular skill acquisition process? This research rests upon the null hypothesis that such an individual can adopt the skill without teaching and language, based on the conclusions put forth by Wynn (among others) (1995). By examining an array of variables concerning both hand-axes and debitage, this null hypothesis will be evaluated with the intent that new hypotheses might be produced for future experiments.

Methods

This study focused on the efforts of a single individual to adopt the knapping technique involved in Acheulean hand-axe production. Prior to the study, the subject had theoretical knowledge of Paleolithic technology and the principles of flint-knapping; this prior theoretical understanding was developed through a one-semester academic course on Paleolithic archaeology as well as several months of perusing the literature as preparation for the project; this did not include practical, hands-on experience with flint-knapping. This prior experience included exposure to both hand-axes and demonstrations of hand-axe making. First, the research subject observed approximately one hour of footage of expert knappers making hand-axes. This included multiple instances of viewing the creation of a hand-axe from start to finish from multiple different expert knappers. The videos in this observation period as well as later observation periods were played without any sound. The intent behind muting the videos was to erase any vocal communication that would provide linguistic information about how to produce a hand-axe. This thus benefited one of the goals of the research, generating hypotheses about the role of language in the learning process behind knapping. Following the observation of experts knapping, I attempted to replicate the technique in independent practice (no expert knappers were present to provide instruction or support). After every 10 hours of practice, there was another 20-minute observation period followed by a documented attempt at producing a hand-axe (during which samples of flakes and other debitage could be collected for measurement). During the course of the study, there was a total of 40 hours of independent knapping sessions, five observation periods, and four documented hand-axe attempts. Hand-axes produced during the practice period were also collected and measured, although no debitage (detached flakes and shatter removed from the core during the reduction process) had been collected during this period. The mineral used as the knapping material for the experiment was obsidian.

In order to develop a record the skill acquisition process, a selection of measurements and ratios were analyzed following the completion of the knapping stage of the experiment. Both hand-axes and debitage elements were measured and analyzed (see Figures 1 and 2).

Hand-axe Measurements

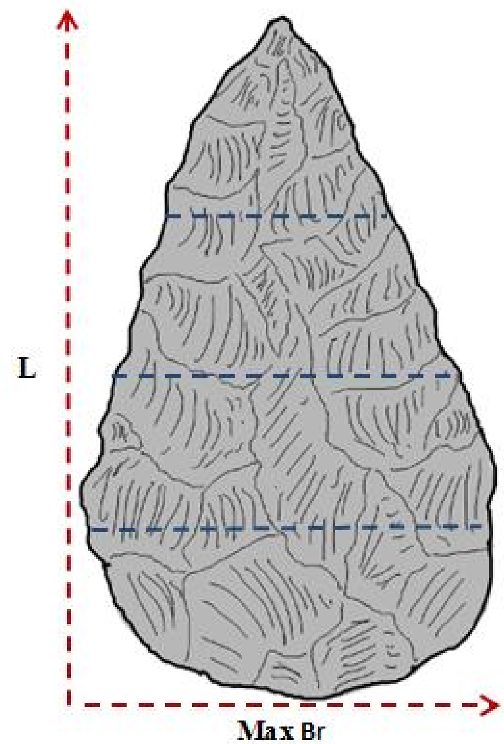

Figure 1 Illustration of three of the primary hand-axe measurements in this study: Max Br (top, red dotted line), L (left, red dotted line), and Br1, Br2, and B3 (top to bottom, blue dotted lines). Th1, Th2, and Th3 were taken at the same increments as Br1, Br2, and Br3, but from the lateral view.

For this study, maximum breadth (Max Br) was measured as the line perpendicular to what was estimated to be the line of symmetry of the hand-axe, extending from the most lateral point on the left side of the hand-axe to the most lateral point on the right sight of the hand-axe. Length (L) was measured as the distance from the base hand-axe to the point, which was presumed to be parallel to the line of symmetry. Maximum thickness (Max Th) was measured as the longest distance between two points on the surface of the hand-axe on z-axis, perpendicular to both the breadth and length measurements (x- and y-axes, respectively). Three breadth (Br1, Br2, and Br3) and thickness (Th1, Th2, and Th3) measurements were taken at increments every

¼ of the total length of the hand-axe. The final absolute measurement considered in this study was total mass of the hand-axes. Each hand-axe like artefact was also examined in order to develop a count of flake scars (indents in the surface of the hand-axe indicating where a flake was removed); the number of flake scars per hand-axe surface area (in mm^2) was used as an approximate measure of hand-axe reduction intensity (on the basis of recent research by Shipton and Clarkson) (2015). Comparison between total volume of flakes produced and the volume of the hand-axes was also utilized to evaluate reduction intensity; volume of hand-axes and whole flakes (which were summed afterwards) was calculated via the following formula: □ = 0.33 (□□1□□1 + □□2□□2 + □□3□□3). Flake scars were counted for the two faces of the hand-axe, as well. The ratio of the higher scar count to the lower scar count was calculated in order to evaluate whether there was disproportionate reduction of either face of the hand-axes and whether the degree of ďlopsidednessô change over time. An additional variable was calculated as a measure of shape: the refinement variable is the ratio of maximum breadth (Max Br) to maximum thickness (Max Th).

Debitage and Flake Measurements

First, the debitage was sorted and categorized before any measurements were taken. Any flake or flake fragment smaller than the dimension of 1cm x 1cm was not measured for this study and was therefore not included in later aspects of the analysis. Those flakes and fragments that equaled and exceeded these dimensions here were sorted into five distinct categories of debitage: whole flakes, proximal segments (flakes fractured horizontally, which include the platform), distal segments (flakes fractured horizontally, which do not include the platform), lateral segments (flakes fractured vertically) and flaked pieces. The latter category primarily consisted of debitage, which lacked identifiable platforms and which could not be concretely identified as distal segments. The ratio of the count of each category of flakes to the total count of flakes was calculated to determine the relative make-up of each set of debitage elements. Of the five categories of flakes and flake fragments, only the whole flakes were subject to further examination and measurement.

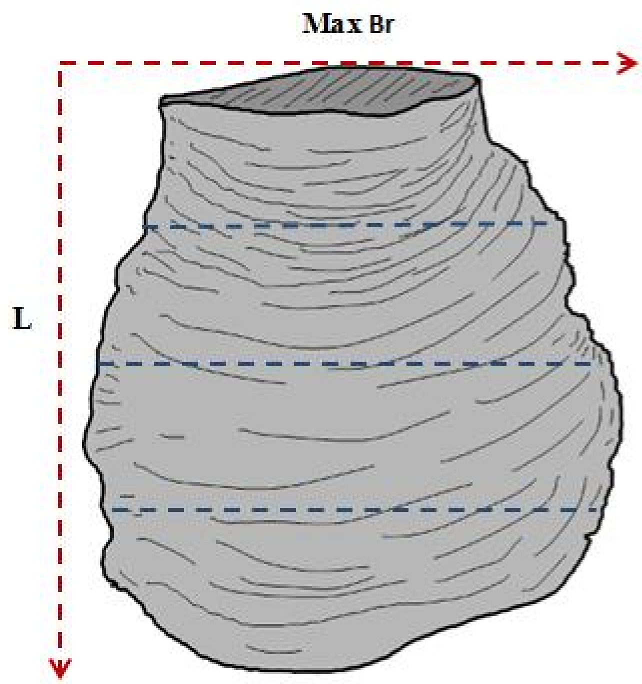

Figure 2 Illustration of three of the primary flake measurements in this study: Max Br (top, red dotted line), L (left, red dotted line), and Br1, Br2, and B3 (top to bottom, blue dotted lines). Th1, Th2, and Th3 were taken at the same increments as Br1, Br2, and Br3, but from the lateral view.

Maximum breadth, length and maximum thickness of the whole flakes (see Figure 2) were measured in a similar fashion to those same characteristics of the hand-axes, with slight variation. Maximum breadth (Br) was measured as the line parallel to the platform which connects the two most distant points on the left and right side of the whole flake. Length (L) was considered to be the maximum distance from the top of the platform to the bottom of the flake perpendicular to maximum breadth (along the y-axis of the flake), and maximum thickness (Max

Th) was the maximum distance from the dorsal surface to the ventral surface of the flake, perpendicular to the two previous measures and along the z-axis. Breadth (Br1, Br2, and Br3) and thickness (Th1, Th2, and Th3) were taken at increments in the same manner as the measurements taken for hand-axes. Three primary platform measurements were taken including: platform breadth (PBr), platform thickness (PTh), and exterior platform angle (EPA).

Qualitative Journal

In addition to these quantitative characteristics, a qualitative journal was kept during the learning period. The purpose of this journal was to record any significant developments, difficulties and other events in the subjective experience of the novice over the course of their acquisition of the Acheulean hand-axe production skill. The qualitative experiences of the novice knapper were then used to inform the analyses and to compare with the quantitative measures, in order to see whether the individualôs experience matches up to the data. Major recurrent themes were also reflected upon for the development of hypotheses and potential research designs for future research.

Statistical Analyses

Statistical analyses based on the data were performed using Statistical Package for the Social Sciences (SPSS) software. From the measurements of maximum breadth and maximum thickness, a value for refinement (the ratio of Max Br to Max Th) was calculated. In order to evaluate the shape of the artifacts, geometric means were calculated for both hand-axes (L, Br1, Br2, Br3, Th1, Th2, and Th3) and whole flakes (L, Br1, Br2, Br3, Th1, Th2, Th3, PBr, and PTh). From the ratio of each individual measurement to the geometric mean, component variables were calculated via principal components analysis (with a cut-off of an Eigenvalue of 1 or above).

This resulted in two component variables for hand-axes and three for whole flakes. For the hand-axe refinement, hand-axe components, hand-axe length, hand-axe mass, reduction intensity, and scar ratio, regression analysis was performed. For the whole flake components, length, and exterior platform angles, one-way ANOVA tests were computed from the means for each knapping session (at 10 hours, 20 hours, 30 hours and 40 hours). Regression analysis was performed for the ratio of whole flakes to total flakes. For each independent analysis, P-values equal to or below 0.05 were considered statistically significant.

Results

Over the course of the 40-hour learning and practice period, a total of 14 hand-axes were produced. Of the 4 sessions in which debitage was collected, two of the sessions failed to produce a hand-axe due to percussion events resulting in the core splitting into two relatively similar-sized pieces. 352 debitage elements (including whole flakes, proximal segments, distal segments, lateral segments, and unidentified fragments) were collected during this study. From these, a total sample of 247 whole flakes was measured: 44 in the session after 10 hours of practice, 59 in the second session at 20 hours, 67 in the third session at 30 hours, and 77 in the final session after 40 hours.

Hand-axes

Hand-axe Shape

The first shape-based variable involved in this study was Br/Th (refinement) (see Figure 3). According to linear regression analysis, the change in refinement over time was not statistically significant ($t = -0.373$, $p = 0.716$). The minor decline ($a = 0.716$) in refinement over the course of the study cannot be interpreted as a significant decrease in this particular measure of hand-axe shape.

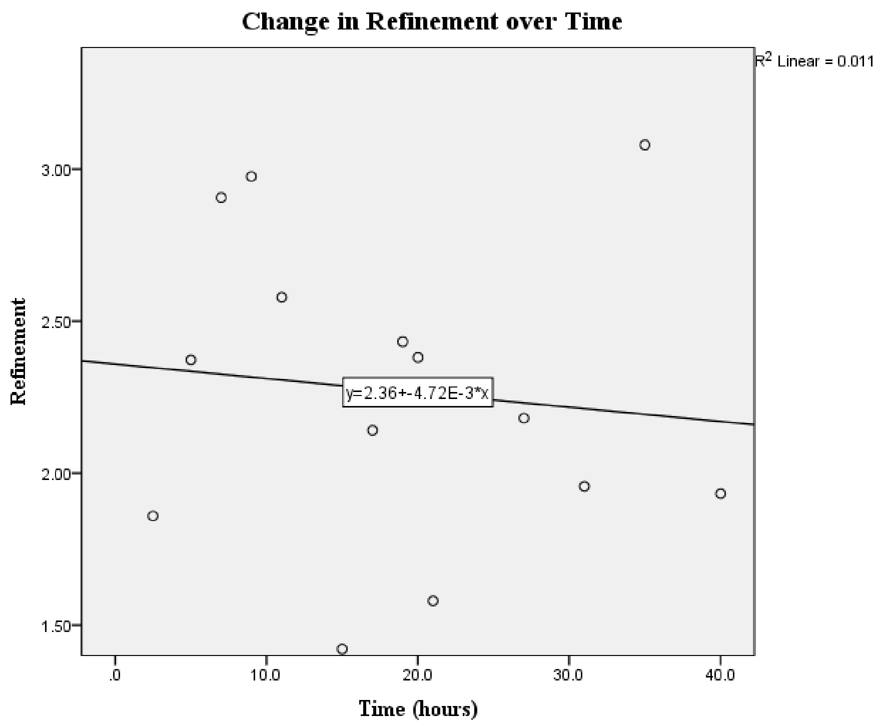

Figure 3 Scatterplot showing the statistically insignificant relationship between refinement and time spent knapping.

Principal component analysis of the ratio of the hand-axe measurements (L, Br1, Br2, Br3, Th1, Th2, Th3) to the geometric mean (see Figures 4 and 5) produced two components explaining the majority of the relationships between the variables and thus providing relative measures of hand-axe shape (Eigenvalue > 1, cumulative variance = 79.437%). Rotation was not employed.

Component variable I summarizes the relationship between distal breadth and distal thickness. As hand-axes become broader on the base end, thickness towards the base decreases. In other terms, broad at the base hand-axes are generally thinner and vice versa. Component variable II summarizes the relationship between length and thickness. As hand-axes become shorter (decrease in L), there is a slight increase in thickness at the tip of the hand-axe (a relatively weak relationship). Shorter hand-axes tend to be thicker on the tip end (thickness measurements Th1 and Th2 are higher in value).

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.020	57.434	57.434	4.020	57.434	57.434
2	1.540	22.003	79.437	1.540	22.003	79.437
3	.747	10.668	90.105			
4	.467	6.667	96.772			
5	.139	1.989	98.762			
6	.082	1.175	99.937			
7	.004	.063	100.000			

Extraction Method: Principal Component Analysis.

Figure 4 Table displaying the total variance explained by the various components produced by the principal component analysis. Note that only the first two components have Eigenvalues of greater than 1.

Component Matrix[a]

	Component	
	1	2
GML	-.152	-.904
GMBr1	.771	.303
GMBr2	.922	.144
GMBr3	.908	-.112
GMTh1	-.640	.548
GMTh2	-.802	.419
GMTh3	-.822	-.348

Extraction Method: Principal Component Analysis.

a. 2 components extracted.

Figure 5 Table showing the various correlative effects for each of the two components.

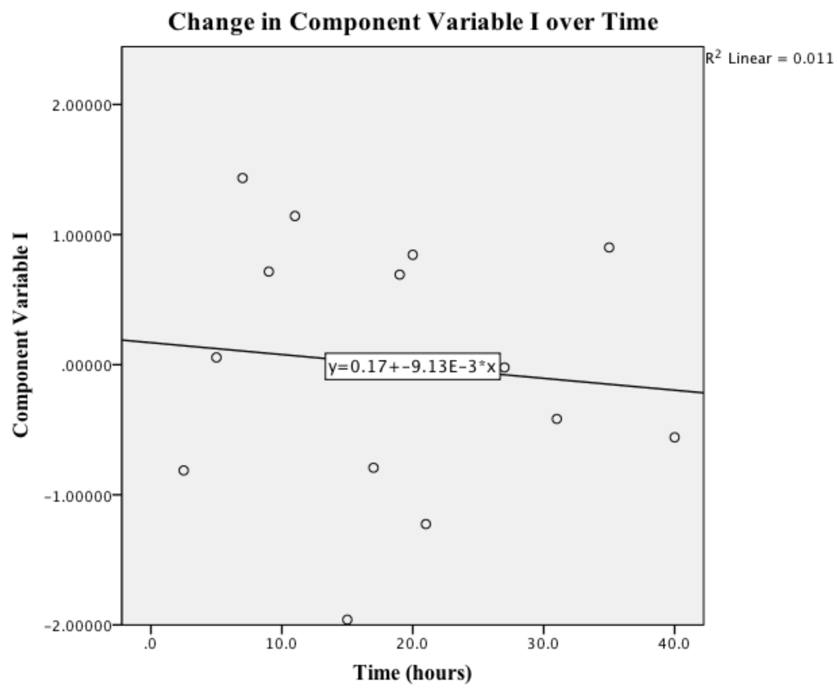

Figure 6 Scatterplot visualizing of the change in the value of component variable I over time spent in knapping practice. Components variable I is a measure of hand-axe shape.

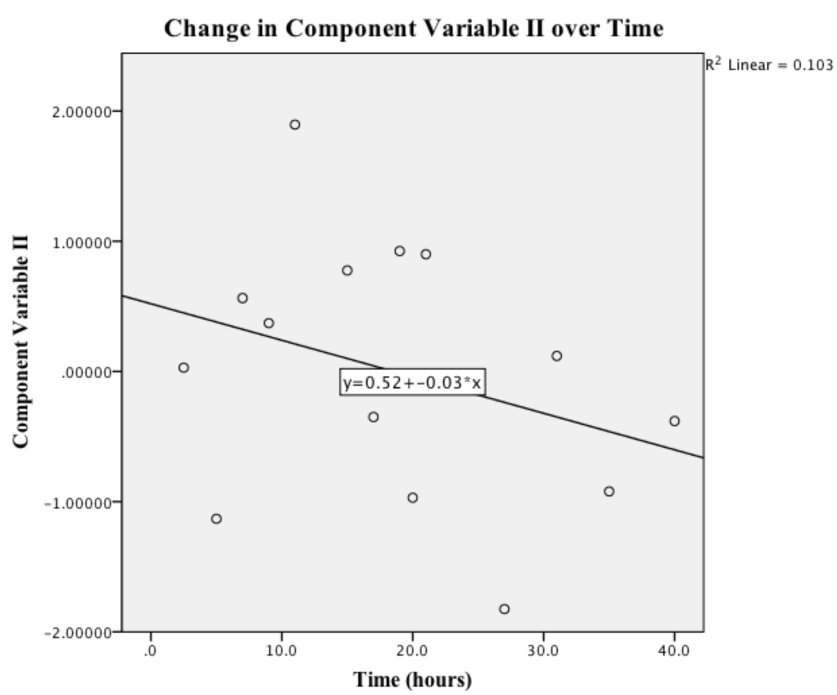

Figure 7 Scatterplot visualizing the change in the value of component variable II over time. Component variable II is another measure of hand-axe shape.

The line defining the relationship between time and component variable I (see Figure 6) has a negative slope ($a = -1.93$). The results of the linear regression analysis are highly statistically insignificant ($t = -0.364$, $p = 0.722$). There is not a significant decrease in the value of component variable I in this time; the shape of the hand-axes in terms of the negative correlation between base thickness and base breadth does not change over time. The line defining the relationship between time and component variable II (see Figure 7) has a slightly negative slope ($a = -0.03$). The linear regression analysis revealed that change in the value of component variable II over time was not statistically significant ($t = -1.174$, $p = 0.263$). Shape of the hand-axe in terms of the relationship between length and tip thickness did not change over the course of the experiment.

Hand-axe Reduction

Based on a linear regression analysis, the change in flake scar density over time (see Figure 8) was not statistically significant ($t = 1.178$, $p = 0.262$). Under the assumption that flake scar density is an accurate measure of reduction intensity (Shipton, 2015), there is not significant development during the 40-hour period with regard to the degree of lithic reduction of the cores.

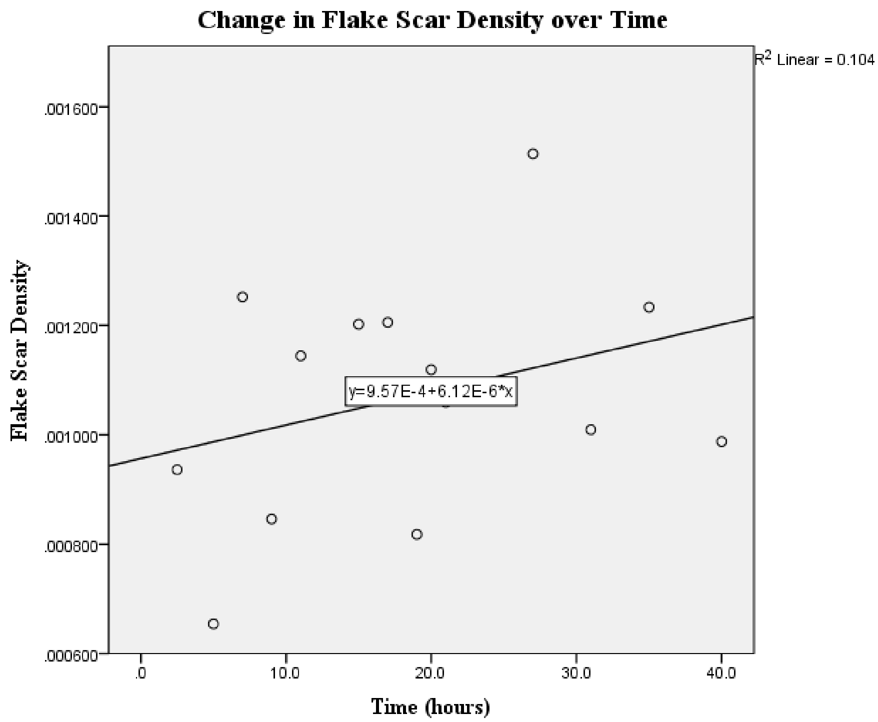

Figure 8 Scatterplot showing the statistically insignificant relationship between flake scar density and time, suggesting a lack of change in reduction intensity during the study period.

As an alternative way of viewing the reduction intensity, the change in volume of both hand-axes and all whole flakes combined (see Figure 9) has been graphed simultaneously. There is an overall decline in hand-axe volume paired with an overall increase in total flake volume. It is noteworthy, however, that changes in hand-axe absolute size were found to be statistically insignificant ($p > 0.05$). Statistical comparison of the two regressions was not performed due to the data that was available; it should be noted that only two of the four samples of whole flakes came from completed hand-axes. This means that the total volume of flakes may not be representative of the ultimate number had the hand-axe been completed.

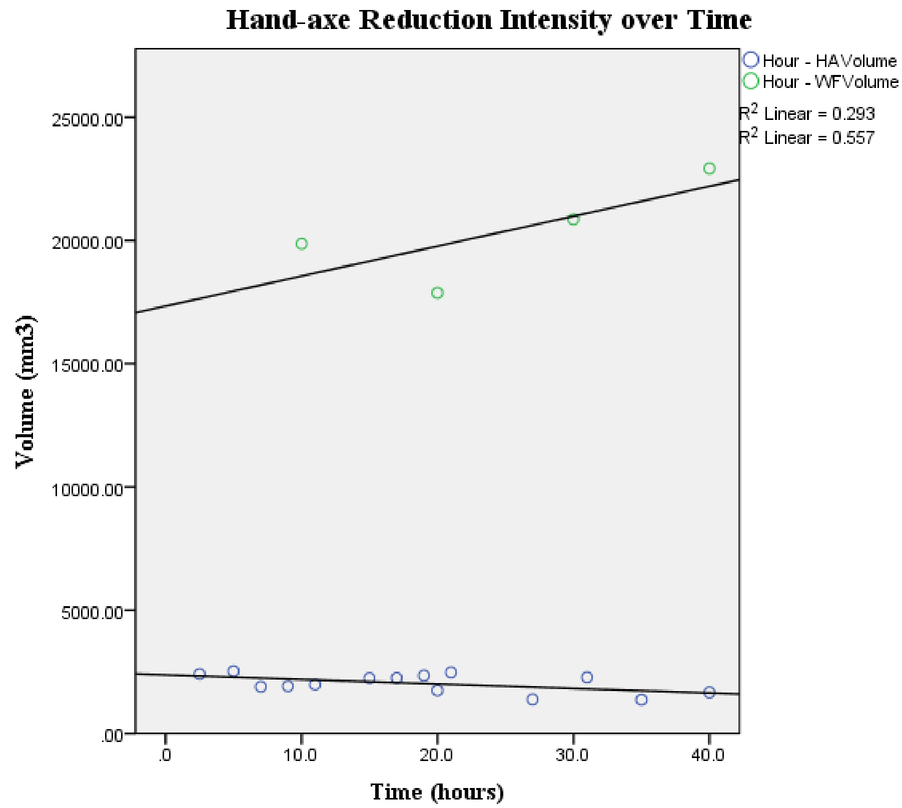

Figure 9 A comparison of change in total volume of whole flakes and the individual volume of the hand-axes.

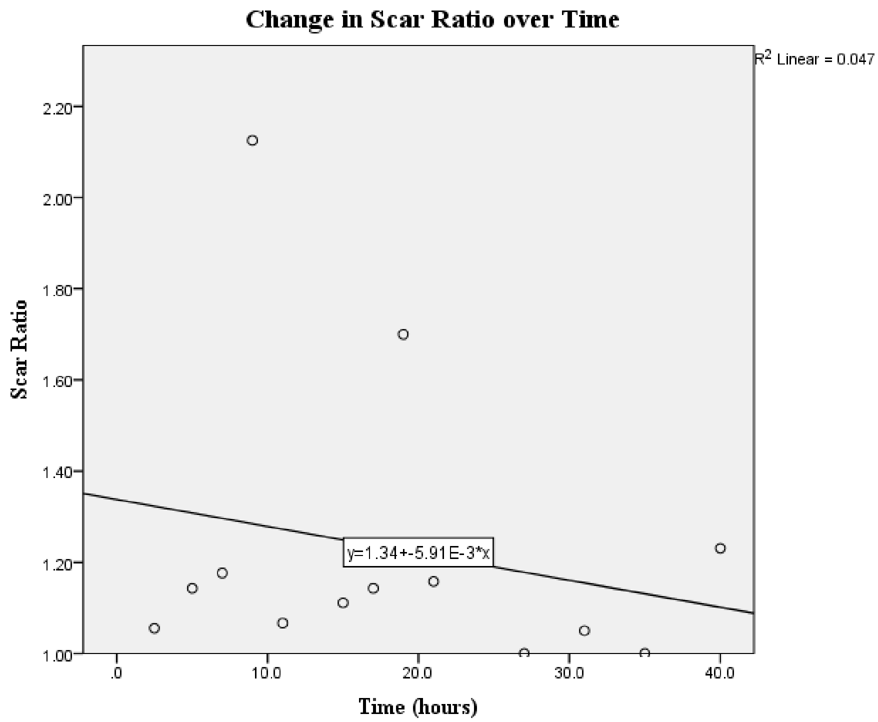

Figure 10 Scatterplot visualizing the change in the ratio of higher scar count to lower scar count over time.

The results of the linear regression analysis revealed that there was effectively no decrease in the degree of disproportionality of reduction over time (see Figure 10) ($t = -0.773$, $p = 0.454$). The scar ratio of hand-axes 4 (9 hours) and 8 (17 hours) stand out as outliers. Both of these outliers fall within the first 20 hours of knapping practice.

Hand-axe Size

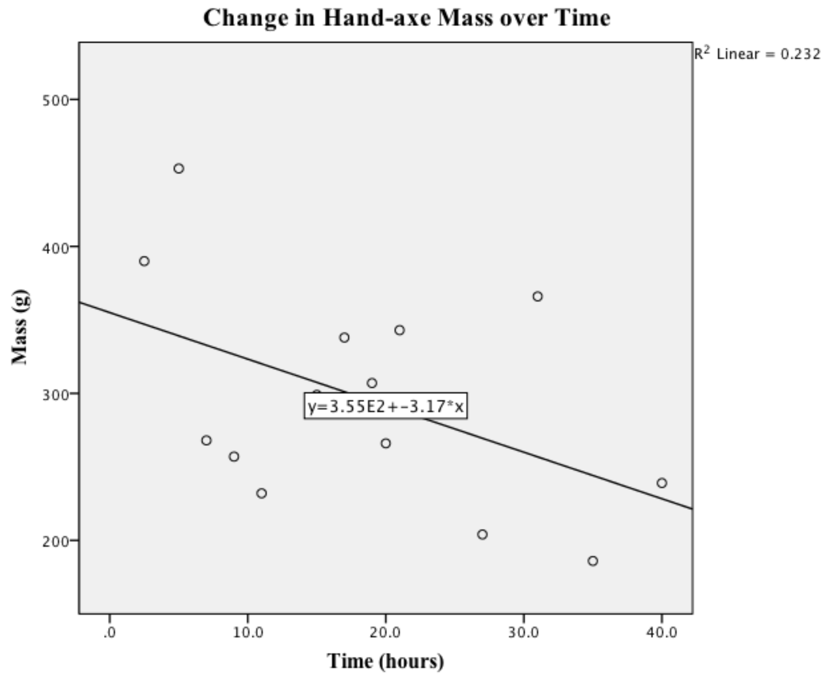

Figure 11 Scatterplot visualizing the change in the total mass (in grams) of hand-axes over time.

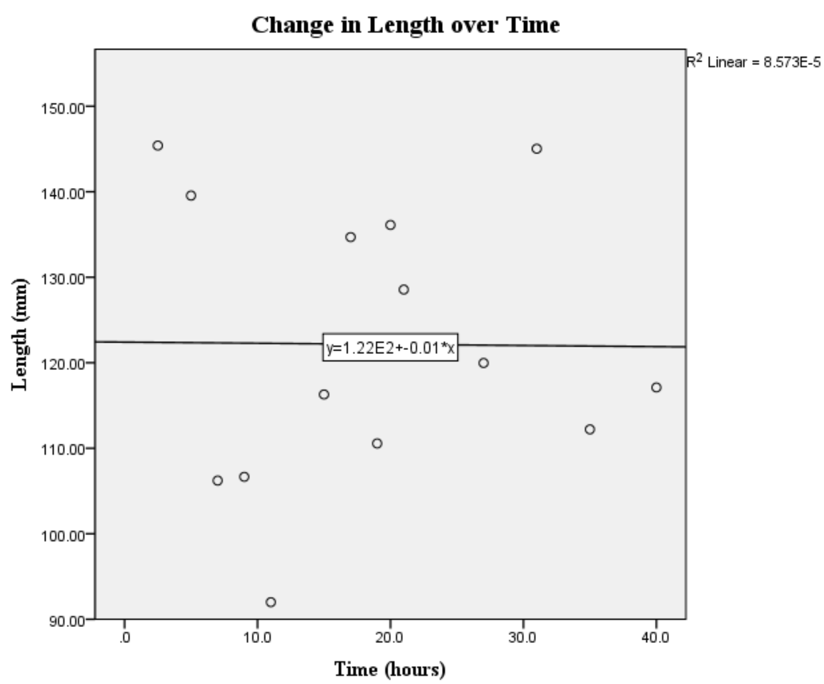

Figure 12 Scatterplot of the relationship between hand-axe length (in mm) and time.

Two measures of the absolute size of the hand-axes were considered for this study: total mass and maximum length. The line defining the relationship between time and hand-axe mass in grams (see Figure 11) has a negative slope (a = -3.17). 16.8% of the variance can be explained by the effect of total time of practice on the total mass of the hand-axe (adjusted $R^2 = 0.168$). The decrease in total hand-axe mass is not statistically significant ($t = -1.905$, $p = 0.081$). The line defining the relationship between time and hand-axe maximum length (see Figure 12) has a marginally negative slope (a = -0.01). There was not a considerable change in the size (maximum length) of hand-axes during the learning period based on linear regression analysis ($t = -0.32$, $p = 0.975$).

Hand-axe Appearance

There were a few subjective qualities of the hand-axes that stand out. Many of the earlier hand-axes (1-8) are relatively flat on one side and convex on the other when viewed in profile. The remaining hand-axes are about equally convex on both sides when viewed with the naked eye. The only exception is hand-axe 16, which is far more convex on one side when compared to the other side, which is relatively flat. Nearly all of the hand-axes (1, 2 6, 8, 9, 10, 11, 12, 14, 15, 16) have step terminations on either one or both of the surfaces. It is uncertain the total number of step termination events that took place during the reduction process for each individual hand-axe as such data was not collected during the experiment. Finally, hand-axes 1, 3, 4, 8, 9, and 15 are notable in that they all have cortex on one of their surfaces. All of these characteristics speak to the degree and quality of the reduction process; besides the increase in lateral symmetry of the hand-axes, there seem to be no observable trends that could be considered evidence of overall improvement or minimally change in the quality of the end product.

Figure 13 Hand-axe 1, produced after 2.5 hours of knapping practice, has cortex (left) and step terminations (right).

Figure 14 The distal end of hand-axe 14, produced after 31 hours of knapping, is characterized by a series of step terminations.

Figure 15 Hand-axes 14(left) and 15 (right), produced after 31 and 35 hours of knapping respectively, demonstrate the degree of observable change in absolute size from one hand-axe to the next. Compared with earlier cores, these hand-axes correspond more closely to the aesthetic qualities of a hand-axe (see hand-axe 4, below, for comparison).

Whole Flakes

During the study, there was not a significant change in the whole flake ratio (ratio of whole flakes to total debitage elements) (t= -0.673, p = 0.570). Although the overall count of whole flakes increased during the study, there was not a change in the composition of the samples (at least when measured by the whole flake ratio) (see Figure 16).

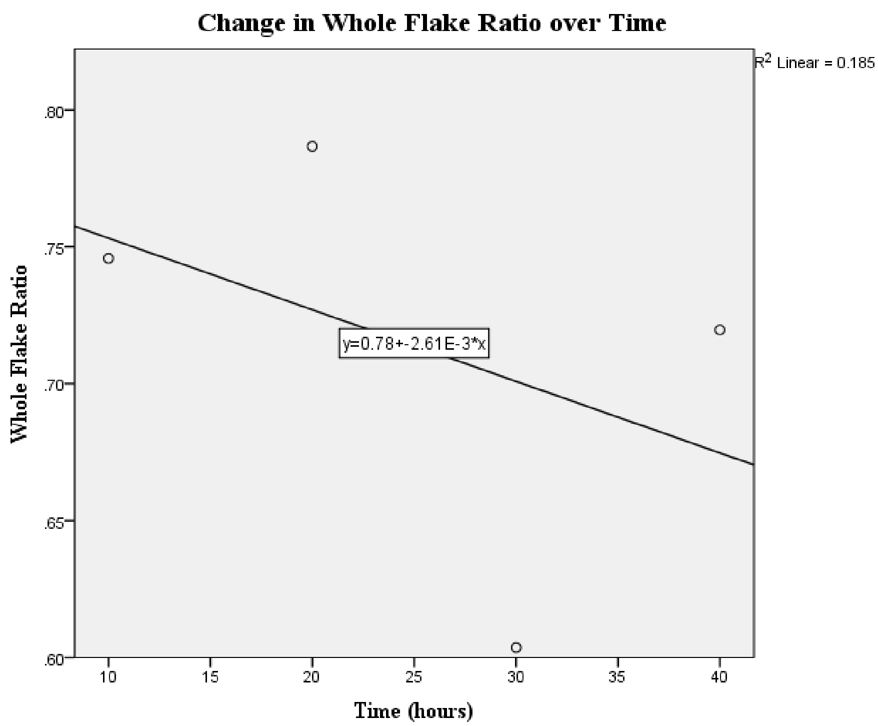

Figure 16 Scatterplot of whole flake ratios over time. Note the minimally negative slope, indicating only a small overall decline in the value of whole flake ratio (a statistically insignificant change).

Whole Flake Shape

Principal component analysis of the ratio of the whole flake measurements (L, Br1, Br2, Br3, Th1, Th2, Th3, PBr, PTh) to the geometric mean (see Figures 17 and 18) produced three components explaining the majority of the relationships between the variables and thus providing relative measures of whole flake shape (Eigenvalue > 1, cumulative variance = 72.396%).

Component variable I summarizes the relationship between whole flake breadth and proximal thickness (including platform thickness to a degree). As whole flakes become broader, proximal thickness decreases and vice versa. Component variable II summarizes the relationship between distal thickness and platform dimensions. Generally, as the dimensions of the whole flake platform decreases (in terms of both breadth and thickness), distal thickness of the whole flake increases. Component variable III summarizes the somewhat weak relationship between whole flake length and distal breadth. As length decreases, whole flakes become broader to a limited degree at the distal end.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.936	32.628	32.628	2.936	32.628	32.628
2	2.472	27.470	60.098	2.472	27.470	60.098
3	1.107	12.298	72.396	1.107	12.298	72.396
4	.798	8.863	81.258			
5	.738	8.202	89.460			
6	.356	3.951	93.411			
7	.291	3.230	96.642			
8	.194	2.156	98.797			
9	.108	1.203	100.000			

Extraction Method: Principal Component Analysis.

Figure 17 Table displaying the amount of variance explained by each particular component, 3 of which have Eigenvalues greater than 1.

Component Matrix[a]

	Component		
	1	2	3
GML	.434	.146	-.832
GMBr1	.673	-.304	-.148
GMBr2	.787	.194	.304
GMBr3	.594	.431	.510
GMTh1	-.767	.053	.022
GMTh2	-.646	.599	.049
GMTh3	-.287	.789	-.053
GMPBr	-.078	-.836	.171
GMPTh	-.478	-.672	.071

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Figure 18 Component matrix indicating the correlations between the different variables.

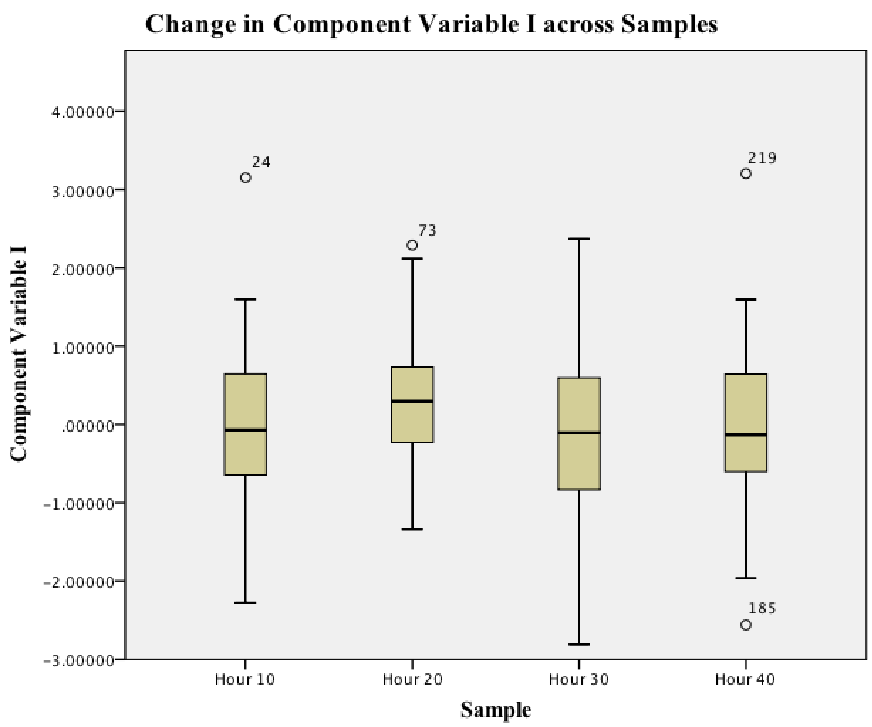

Figure 19 Boxplot visualizing the distribution of component variable I values in the four sets of whole flakes.

Based on a one-way ANOVA test, the mean value of component variable I (see Figure 19) was not significantly different across the four hand-axe producing sessions ($F = 1.638$, p =

0.182). Shape of the whole flakes in terms of the inverse relationship between flake breadth and proximal thickness did not increase or decrease during the 40-hour period.

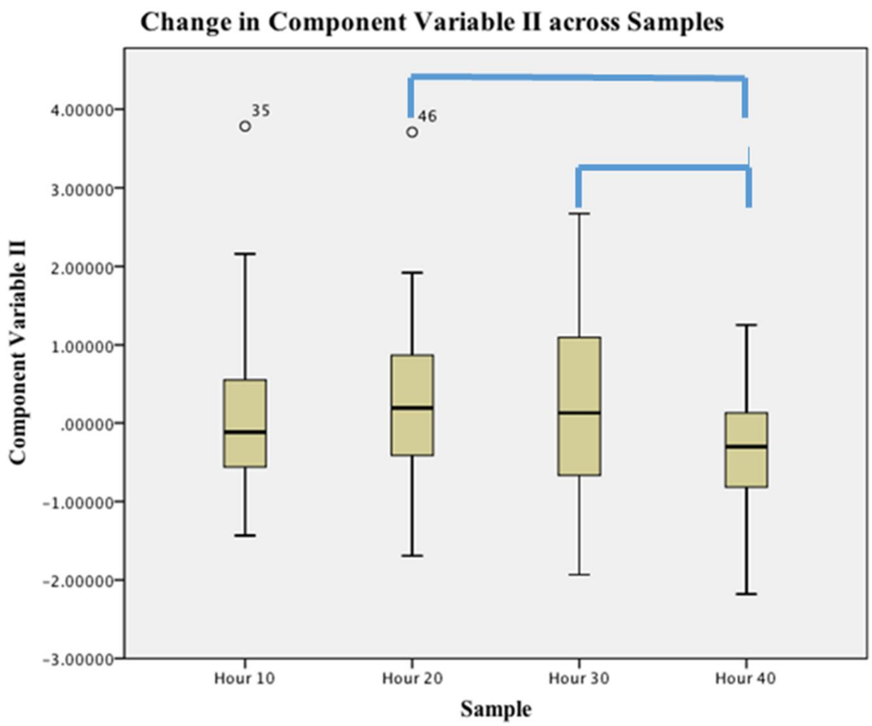

Figure 20 Boxplot visualizing the distribution of component variable II values in the four sets of whole flakes. Brackets indicate significant pairwise differences ($p < 0.05$).

A one-way ANOVA test of component variable II (see Figure 20), revealed a change in the value of component variable II over the course of the study ($F = 6.113$, $p = 0.001$). There was a change in whole flake shape, which involved an initial increase in the value of component variable II from hour 10 to hour 20 followed by a decrease after hour 20 (a non-linear development). Whole flakes towards the beginning and at the end of the study had relatively lower distal thickness and larger platform dimensions. The opposite was true of whole flakes at hours 20 and 30, more so for hour 20. A Tukeyὃs HSD test confirmed this pattern as being statistically significant. The mean value for Hour 20 was greater than for Hour 40 ($p = 0.002$).

Likewise, the mean value for Hour 30 was greater than for Hour 40 (p = 0.003). There was no significant difference between Hour 10 and the other samples.

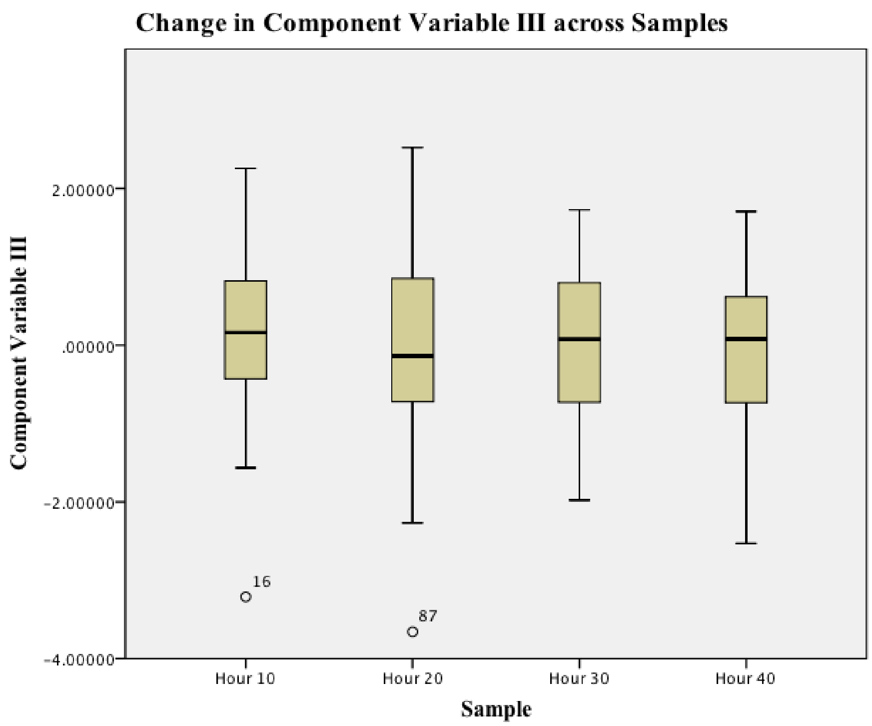

Figure 21 Boxplot visualizing the distribution of component variable III values in the four samples of whole flakes.

According to a one-way ANOVA analysis, the difference in values of component variable III (see Figure 21) during the study were statistically insignificant (F = 0.146, p = 0.742). Therefore, the shape of the whole flakes in terms of the weak negative correlation between flake length and distal breadth did not change from hour 10 to hour 40.

Whole Flake Size and Platform Angle

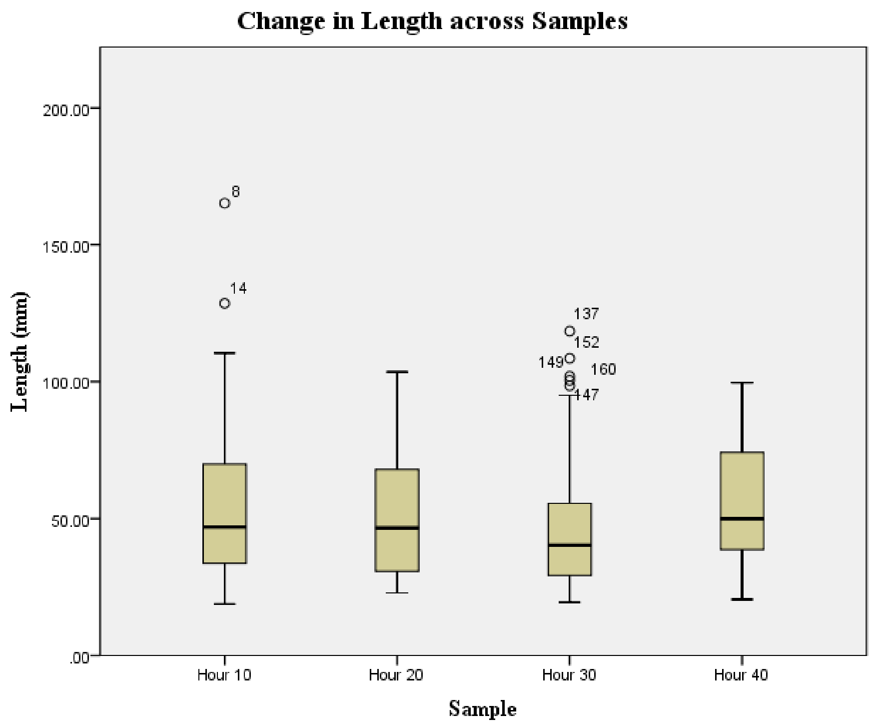

Figure 22 Boxplot showing the distribution of whole flake length in the four samples collected during the study.

As a means of tracing the change in absolute size of the whole flakes, ANOVA analysis of the maximum length of the flakes (in mm) was performed (see Figure 22). The analysis revealed that there was not a considerable change in the mean length of the flakes across the four samples ($F = 1.779$, $p = 0.152$).

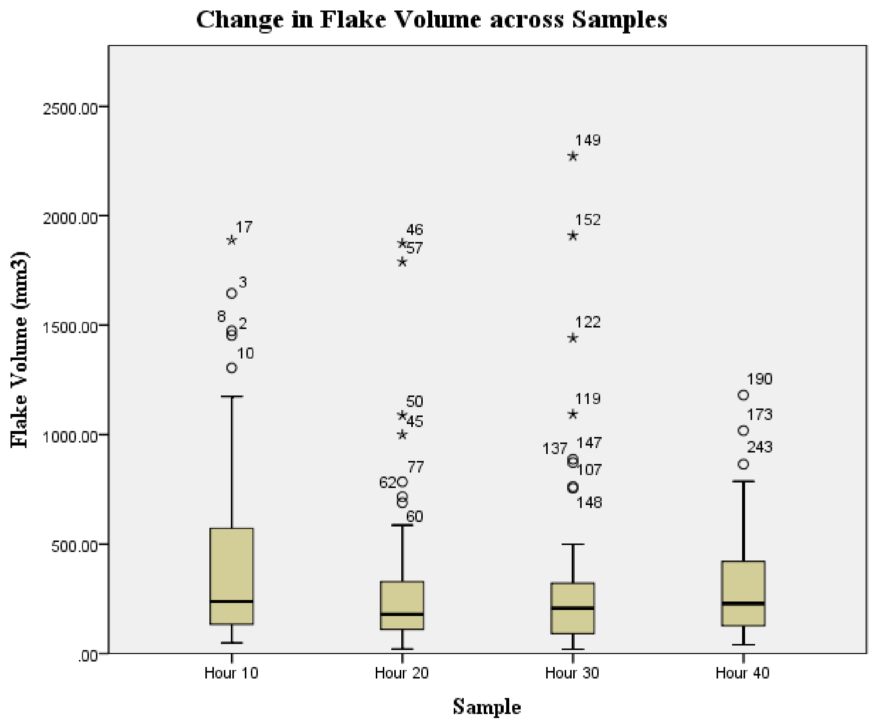

Figure 23 Boxplot showing the distribution of whole flake volume in the four debitage samples.

An additional measure of absolute size evaluated in this study was whole flake volume (see Figure 23). Across the four samples, there was not a significant difference in the volume of the flakes in mm^3 ($F = 1.999$, $p = 0.115$). When viewed in conjunction with the increase in whole flake count (but not whole flake ratio), more flakes were produced over time, but the flakes themselves remained relatively similar in size from beginning to end.

A one-way ANOVA test comparing the mean of platform area across the four flake samples (see Figure 24) revealed a statistically significant change in the total area (mm^2) of the whole flake platforms ($F = 3.681$, $p = 0.013$). There was not an emergent pattern in these differences as all pairwise differences were statistically insignificant ($p > 0.05$).

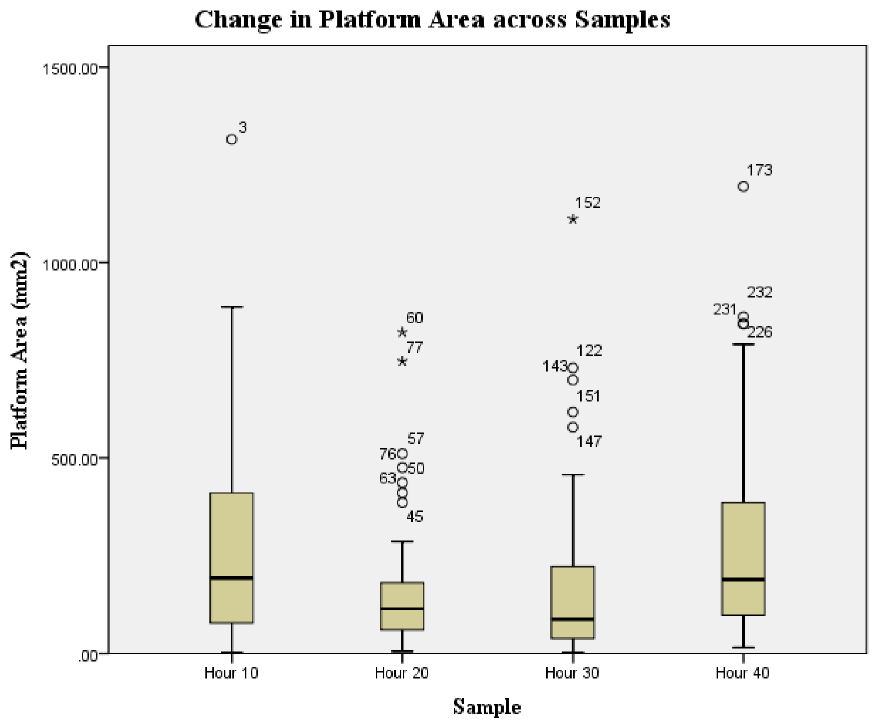

Figure 24 Boxplot displaying the distribution of platform area for each of the four samples.

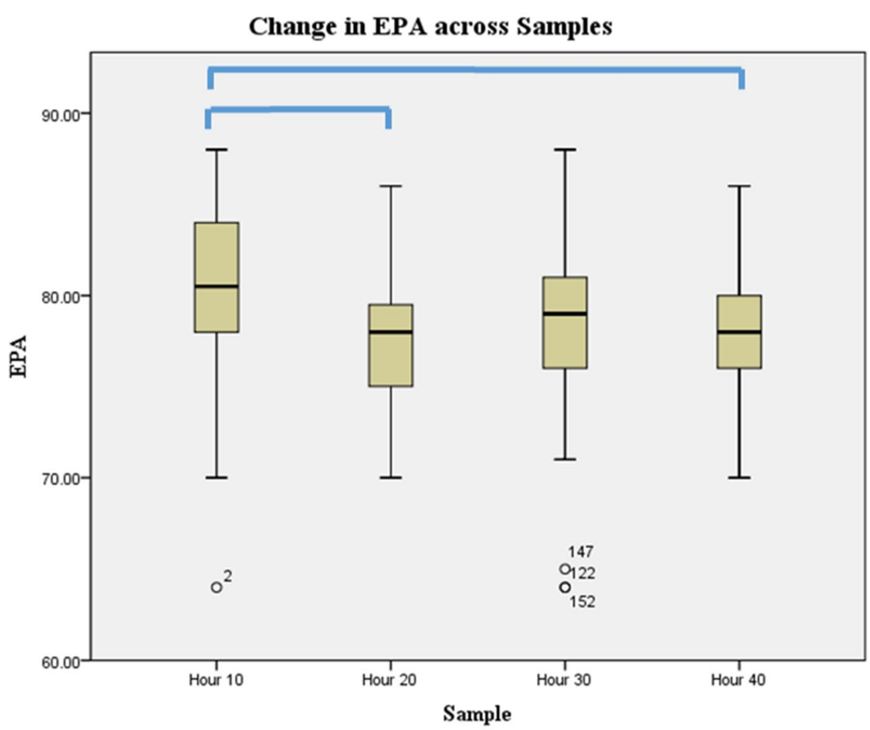

Figure 25 Boxplot visualizing the distribution of the exterior platform angle of whole flakes in the four samples. Brackets indicate statistically significant pairwise combinations.

Based on a one-way ANOVA analysis, the difference in the mean value of the exterior platform angle (EPA) across the four samples (see Figures 25) was statistically significant ($F = 3.356$, $p = 0.020$). These results indicate that there was an overall decrease in the mean exterior platform angle (although there is a notable increase in the mean of EPA from hour 20 to hour 30); this decrease was statistically significant based on post-hoc Tukey HSD analysis ($p < 0.05$) for the difference between Hours 10 and 20 and Hours 10 and 40.

Qualitative Journal

From the qualitative journal kept by the subject during the learning period, a selection of events, developments, and difficulties have been highlighted due to potential elucidation they could provide for future research. These themes have been organized into a timeline, which shows the progress (and lack of progress) over the course of the study (see Figure 26).

Perceived Difficulties

One of the more notable results of keeping a qualitative journal were the list of themes pertaining to perceived difficulties experienced by the subject (and the management of such difficulties). The most frequently mentioned difficulties included:

1. **Selection and appropriate application of hard and soft hammers:** The appropriate selection of the different hammers (small and large hard hammer and soft hammer) for different stages of the reduction process was a major problem for the subject, especially early on in the learning process. In the earlier part of the knapping practice, the hard hammers were used relatively interchangeably, due to a lack of a concrete understanding of how and when to properly use them. Further into the process, there was degradation of the small hard hammer, which may have been a consequence of novice knapping technique or the quality of resources at the disposal of the

subject. This degradation was the cause of dust production. The subject was unable to master the use of the soft hammer percussion technique, and viewing expert knappers using soft hammers provided no major benefit. After approximately 25 hours of lithic reduction practice, the soft hammer was abandoned.

2. **Control of percussion:** Amount of force, angle of percussion, and accuracy of percussion were all issues that plagued the early stages of the knapping skill acquisition period. Inability to control the force behind the blow intending to produce flakes resulted in mistakes during knapping, such as cases where a heavy blow split the core into two parts, the size of which were too small to produce hand-axes. Issues with control over the percussive event also would result in step fractures, which were perceived to have occurred with greater frequency after the early stages of the learning process.

3. **Producing a biface:** There was a perceived difficulty in achieving an end product that was a biface; to the subject, it seemed that one side of the hand-axes tended to be more heavily reduced than the other, especially earlier on in the experiment. However, the results of the scar ratio analysis (no significant decrease in the scar ratio over time) seem to contradict the subjective experience of the novice knapper. Related to both this problem and the issue with control over percussion, the subject was unable to maintain a flat plane during the knapping practice sessions.

4. **Judgment of resource quality:** Generally, the research subject was unable to determine what size and quality cores would be useful or even capable of becoming hand-axes. The inability to evaluate resource quality seemed most problematic during the last several hours of knapping practice. However, the perception of poor quality obsidian may not reflect the actual quality of the material itself. These issues could simply be attributed to the lack of ability to appropriately use available resources rather than resources being unusable.

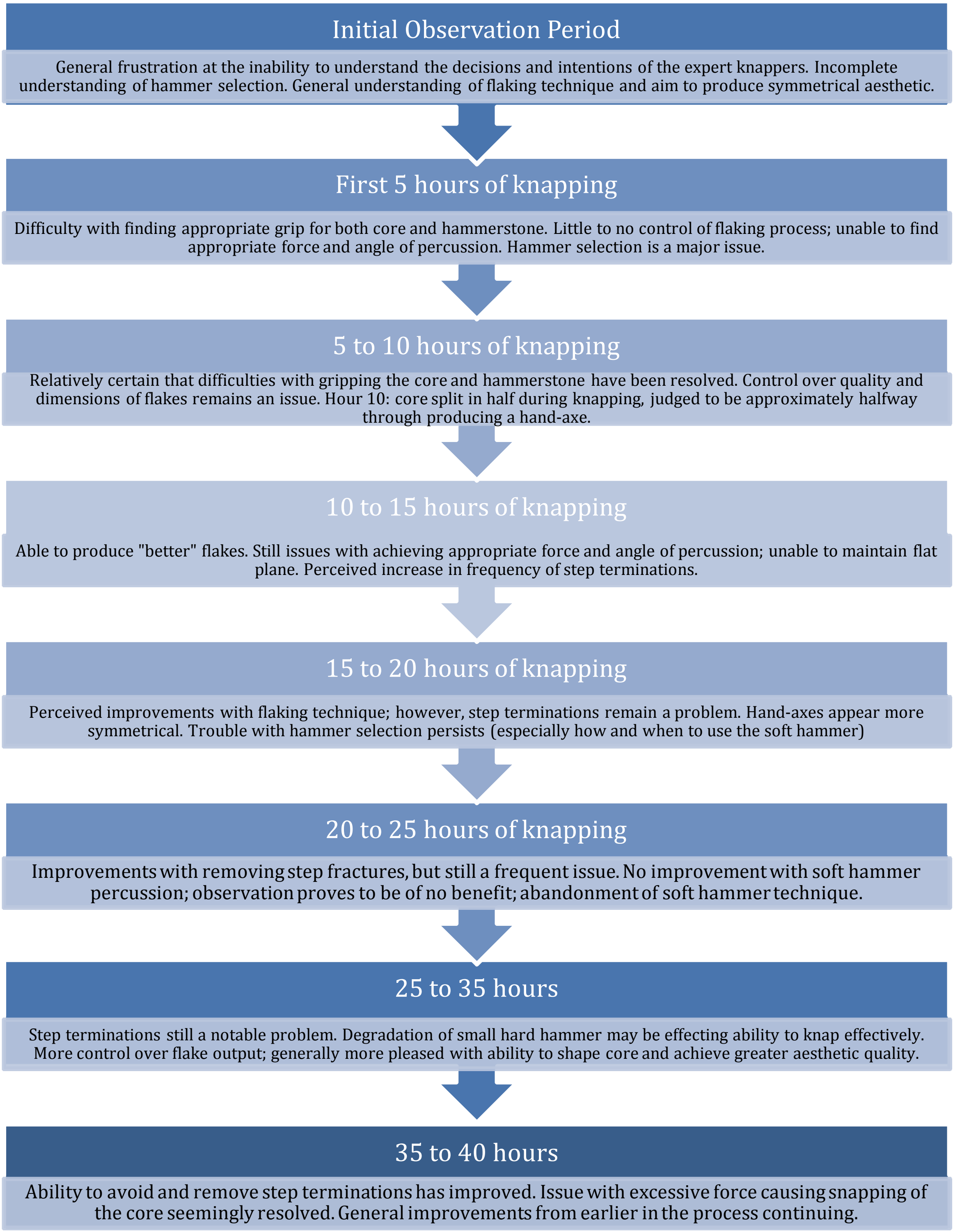

Figure 26 Timeline of major developments during the 40-hour learning period.

Discussion

Social learning is a major aspect of cognition involved in accumulation of culturally defined skills. For this reason, we can study the evolution of cognition by examining the kinds of social learning mechanisms involved in learning how to make a hand-axe (from emulation and imitation to fully realized progressive teaching and language skills). In response to the main question of this study, specifically whether an individual could potentially take up the Acheulean hand-axe-making skill via a learning process absent teaching or language, the answer is a resounding *maybe*. Minimally, this study reveals that there is little distinguishable progress as far as the hand-axes and only slightly more significant change with regard to the whole flakes (potential experimentation with how to strike the platform). In addition, the results of this experiment suggest that the learning process without direct teaching or linguistic input is at least difficult, if not partially impossible (such as soft hammer percussion). From these results, emulation/imitation learning allows for the adoption of some aspects of the Acheulean knapping technique but not all aspects. Within this discussion, I aim to a) interpret the results, b) tie these results back to recent research in this emergent field, c) compare the results with data from the archaeological record, and d) present a research plan for a potential future study.

Interpreting the Results

During the course of the study, there was very limited change in the measures of hand-axes, including the component variables for hand-axe shape, the scar ratio, and the indicators of absolute size (hand-axe length and total mass). As far as the indicators of hand-axe shape, other potential measurements should be investigated, beyond those included in this study. An example of a new measurement that may benefit the study would be additional length measures, perhaps in the same vein as the breadth and thickness measurements (in increments of ¼ of the maximum breadth of the hand-axe). From the measurements examined in the study, only two components were found using the principal component analysis, which means only two measures of hand-axe shape were used in this experiment. Additional caliper measurements may therefore produce additional shape variables for future analysis.

The intent of performing scar counts was to evaluate the degree of reduction on both sides of the hand-axes and to see whether the ratio of reduction between the two sides changed as the experiment progressed. The lack of significant change (specifically a decrease) in scar ratio would seem to indicate that the imbalance in reduction of the two faces did not improve greatly in the learning period. The results of this analysis are not conclusive, however, as alternative measures of bifacial reduction were not investigated in this study. More direct (as opposed to subjective) examinations of lateral symmetry and hand-axe cross section shape, when compared with the results of the scar ratio analysis, could prove beneficial in determining the extent of bifacial reduction during the skill acquisition process. Utilization of either the flip test for lateral symmetry or Elliptical Fourier Analysis of cross-sectional shape is recommended for future examination (Hardaker and Dunn, 2005; Putt, Woods and Franciscus, 2014). It may also be beneficial to compare the proportion of the hand-axe surface that is still cortex as an additional measure of reduction intensity.

Linear regression analyses of hand-axe length and mass revealed that there was not a general trend for changes in hand-axe size (either an increase or decline in size). However, there was a noticeable change in hand-axe mass (albeit statistically insignificant; $p = 0.081$). Because of the nearly statistically significant change in this variable, it may be beneficial to look more closely at mass in future research. Subjective evaluation of the characteristics of the hand-axes in the study would also suggest that there was very limited development, except for observable changes in cross-section shape; later hand-axes were generally less lopsided, with both sides of the hand-axe (when viewed laterally) appearing to be about as convex as one another. Improvement in hand-axe symmetry in the study by Putt, Woods and Franciscus would indicate that symmetry develops in both verbal and nonverbal conditions, but this did not seem to be the case for nonverbal conditions based on qualitative assessment in this study (2014). Changes in cross-section shape likely resulted by overcoming certain errors typical of inexperienced knapping, such as lack of control over shape and mistakes in generating a bifacial edge (Schick, 1994).

The same can be said of many of the quantitative indicators examined for whole flakes, with component variable II for whole flakes and exterior platform angle standing out as outliers. The values of components variable II indicate that flakes towards the beginning and end of the study had larger platforms and were thinner towards the distal end. The non-linear progression of component variable II is difficult to interpret; however, the increase in value followed by decrease in value of component variable II might suggest that learning how to make a hand-axe (at least without verbal and gestural communication) does not progress uniformly in a linear direction. Specifically, there was some sort of change and then reversal with regard to how the cores were struck with the hammerstone to create such larger platforms and lessened distal thickness. The overall decrease in the mean exterior platform angle from hour 10 to hour 40 suggests that there was overall improvement in the subjectǿs ability to achieve appropriate angles of percussion during the reduction process. Achieving more acute platform angles has been demonstrated as an indicator of increased time spent practicing knapping technique (Stout and Chaminade, 2007). However, it is hard to distinguish whether the intent to achieve increasingly more acute angles was solely a result of increased practice or if the theoretical knowledge from before the study might have promoted this development as well. When the changes in flake shape, platform area, and platform angle are viewed in conjunction, it suggests that there was a degree of experimentation with regard to the percussive events (the amount of force, angle of percussion, selection of hammerstone, etc.). This sort of experimentation (indicating a lack of complete control over the flaking process) is indicative of limited skill development (Nonaka, Bril and Rein, 2010). This limited skill development in terms of flaking control under asocial, non-linguistic conditions promotes the hypothesis that learning how to make a hand-axe would have benefited from verbal input and teaching.

The lack of directional change in the other measures studied here suggests an overall stagnation of skill development, at least in this study. At face value, the overall lack of significant changes during the learning period may be interpreted to mean that there is something about an asocial, non-linguistic environment that leads to a stagnation in the acquisition of the Acheulean hand-axe-making skill; in other words, without any guided instruction and social influences, novice flint-knappers are limited in their ability to adopt this technological complex, or they at least experience stunted development due to their learning conditions. This conclusion is reflected in the struggles experienced by Callahan when initially attempting to learn how to make hand-axes in a time where there was very limited understanding of the actual reduction process:

> When I started down the road of lithic technology in 1956, I had no idea that bifacial reduction of a stone tools required more than straight-forward circumferential flaking of a piece of flint. [in fact this is the strategy adopted by non-verbal group in Puttǿs study] Without any textbooks other than original stone artifacts to guide me during my first 10 years of flintworking, I had to guide myself through two million years of biface reduction discovery. I knew nothing of the principles required to produce width/thickness ratios to the tolerances seen on artifact originals except as I stumbled upon those principles by trial and error. In time I came to grasp principles which would allow me to create credible replicas of Oldowan Choppers, Abbevillian Handaxes, Acheulean Handaxes and, finally, Solutrean Laurel Leaves and New World projectile points and bifaces.

> For years, as I attempted to evolve from an ñAbbevillianò level of biface technology to an ñAcheuleanò: level, I achieved nothing but smaller and relatively thicker Abbevillian-like bifaces. That is, as I worked on a given biface, it became narrower and shorter without becoming correspondingly thinneré When, in time, I discovered billet flaking, platform preparation with a coarse abrading stone, and a striking angle near perpendicular to the center plane of the biface, I was able at last to create Acheulean-like bifaces at will. Technologically, replicating the Acheulean Handaxe was a major step forward in the evolution of my control of stone. (1979)

Interestingly, there is considerable overlap between the self-reported difficulties during this experiment and frequent errors experienced by novice knappers as previously noted in the archaeological literature (Schick, 1994; Shelley, 1990). The errors observed by Schick include:

> Removing too much width before the piece is adequately thinned (producing thick, narrow, even quaduhedral products), failure to maintain a good plane (e.g. producing bowed or extremely sinuous bifaces or just a lot of flake waste and an amorphous core), poor control over the outline shape, failure to extend the bifacial edge through more obtuse areas of the blank, removing the tip end through uncontrolled flaking, [and] breaking the biface in half with too strong a blow after it has been substantially thinned. (1994)

The latter two errors were certainly present in two of the knapping sessions (after 10 hours and after 30 hours). The other errors were persistent throughout the experiment. In his work on lithic assemblages, Shelley highlights the higher frequency of step terminations (especially stacked step terminations) and unsuccessful flake removals on cores produced by beginners as opposed to those produced by more seasoned knappers. Both of these errors may be attributed to a lack of the motor skill necessary for mastering the fracture mechanics of knapping by inexperienced knappers, such as misapplication of force and angle of the blow resulting in uncontrolled flaking (Magnani et al., 2014). This infers that a practical motor skill of percussion flaking is necessary for the development of said skill. This suggestion is promoted by the conditions in this study; the subject had extensive theoretical knowledge of Paleolithic technology and knapping, but when faced with the task of learning how to make a hand-axe, still faced many of the difficulties of knapping derived from a lack of the precise skill required for fracture mechanics. This prior experimental evidence for many of the difficulties and mistakes encountered by the novice in this study suggests that these errors may be typical of unskilled lithic products in any learning condition, although, naturally, further evaluation of this hypothesis is necessary.

Language, Social Learning and Hand-axes

As stated previously, the intent of this pilot was to elaborate upon previous research into the social learning mechanisms and role of learning in the adoption of the skill of Acheulean hand-axe production. Two recent studies, one of which investigated social learning and the Oldowan and the other of which examined the relationship between verbal instruction and learning how to make a hand-axe, have drawn drastically different conclusions about the role of language in the Acheulean technological complex (Morgan et al., 2015; Putt, Woods and Franciscus, 2014). Morgan and colleagues, on the basis of their analysis of the social transmission of Oldowan technology, propose that the transition from the Oldowan industry to the Acheulean would have required the evolution of teaching and language-like mechanisms to ensure high-fidelity transmission of the technique. Alternatively, Putt, Woods, and Franciscus found that learning how to make a hand-axe was equally as successful under both verbal and nonverbal conditions; therefore, language would not have been a prerequisite for the production of Acheulean artifacts.

One of the most important caveats for both studies is the short duration of the teaching/learning period (which Putt, Woods, and Franciscus fully acknowledge in their article). As previously discussed, the learning period in the former study was under half an hour, and the teaching/learning period in the latter study amounted to a total of five hours. This leaves open the possibility for divergence between groups of varying social and linguistic conditions in terms of learning development after this short initial period. The quality of the teacher is also a major issue in the first study; the shorter duration of the learning period would suggest that the individual providing instruction or serving as the learning model may not be a true expert, which would potentially reflect on the abilities of the individual being tutored to replicate a technique. The manner in which both non-human primates and humans seek experts as models when learning to adopt new behaviors promotes the inference that ancient hominins would have as well. For this reason, the ñtelephone gameò-style study design for which these researchers has opted does not necessarily replicate the means of transmission utilized by human ancestors. Putt and her fellow researchers also limited their experiment to two learning environments (unlike Morgan and colleagues, who examined five different forms of transmission settings): one with verbal instruction and one without verbal instruction.

During this experiment, the overall count of whole flakes per sample increased while the size of said flakes remained about the same (no statistical significance for the differences in mean length across samples). Although change in debitage counts (though not composition) can be accounted for by resource constraints, the increasing amount of relatively same-sized flakes would infer that there is a deficiency in the ability to achieve the goals of biface production in the first 40 hours of learning in a nonverbal environment; continuous production of these flakes leads to excessive reduction of hand-axe breadth without a coinciding decrease in thickness, creating an end-product that is disproportionately thick and unwieldy (Schick, 1994). This aligns with the results of Putt and colleaguesô study but reaches a separate conclusion; without proper guided instruction, individuals learning to knap in conditions without verbal input and feedback have difficulty with imitating the chaîne opératoire of Acheulean hand-axe making.

Inexperienced knappers seem to have a general lack of practical understanding of the physics and mechanics of lithic reduction; a theoretical understanding of what needs to be done and the actual motor skill required for hand-axe production may be uneven in their rate of development. This is a notable conclusion for this study, because the subject already had prior theoretical knowledge of lithic technology, but when the actual learning period began, there was still substantial difficulty in adopting the technique. This lack of improvement in terms of flake efficiency would seem to indicate that the early differences between verbal and nonverbal conditions could have longer term consequences not observed by these researchers in the first few hours of skill development.

Without alternative conditions with which to compare, the asocial, nonlinguistic learning conditions experienced by the subject in this pilot study would seem to fall in line more closely with the results and conclusions put forth by Morgan and colleagues (2015). The relative stagnation of learning development during the 40 hours of the experiment seems to indicate that the lack of verbal communication and active feedback during the learning process is detrimental to skill acquisition. This does not necessarily mean that the results of this study are incompatible with those of the Putt, Woods and Franciscus study as the time scale is larger and the social learning conditions are different, although not markedly so, due to the physical presence of an instructor as well as a cohort of other novices. This remained true even when the subject in an asocial, nonlinguistic environment had previously been instructed about Acheulean technology and knapping on a theoretical and academic basis.

Based on how the various mechanisms of social learning were previously defined, I would interpret how the hand-axe making skill was acquired as falling somewhere between, or a combination of, emulation and imitation. One of the main forces driving the interpretation of this learning process being emulative was the general inability to fully copy the particular steps in the reduction process. This is especially true of the subject being unable to master soft hammer percussion technique and fully abandoning the antler billet after only 25 hours of knapping practice. Prior knowledge of hand-axe aesthetics, proximity to hand-axes and the related debitage, and the availability of resources for independent practice suggests that, despite direct social interaction, learning took place in an environment typified by niche construction (Fragaszy, 2013). Despite presumed deficits in terms of lack of teaching individuals, the learning environment remained generally conducive to the skill acquisition process.

Experimental Replication and the Archaeological Record

How do the artefacts from this study compare with those found in the archaeological record? It is important to discuss what implications this study might have for our understanding of the archaeological record and vice versa. By viewing the experimentally replicated artefacts in light of those produced by hominin toolmakers of the Acheulean, the replicas can provide insights about the social learning capacities of different hominin populations, separated by time and by geographic space. Based on data published by Beyene and colleagues (2013), the hand-axes produced during this experiment are in line with hand-axes from around 0.85 million years ago in Konso, Ethiopia (as opposed to hand-axes earlier in the Acheulean): the mean refinement (thickness to breadth) and flake scar count of hand-axes at KGA20-A1 and A2 are 2.13 and 30.4 respectively, compared with average values of 2.18 and 35.1 from hand-axes from this study. The lack of significant development in either flake scar density or refinement over the course of this study imply a lack of skill development, at least as defined by Beyene and fellow researchers (increasing flake scar count without significant change in refinement). A further comparison with hand-axes from Boxgrove, UK at approximately 0.52 to 0.48 million years ago (Stout et al., 2014) helps further situate these experimentally-produced artefacts within the archaeological timeline; the hand-axes from this site have a mean refinement of 2.6, which is greater in value than either the Konso specimens or the objects from this study (and further falls somewhere between experimentally replicated hand-axes produced by óexpertô and ónoviceô (or intermediate) knappers. Boxgrove hominins may have been required learning and language capabilities that were unavailable to the learner in this study (although one might disagree at the degree of disadvantage; e.g., contemporary humans are linguistic animals by nature). The similarities between the hand-axes from this experiment and those in the earlier parts of the Acheulean and the emerging differences between the replicas and the hand-axes from the later Acheulean of Boxgrove imply that there were possible key evolutionary developments that occurred with regard to social learning or language within the Acheulean rather than at the boundary of the Oldowan and Acheulean, as suggested by Morgan and colleagues (2015).

One of the key debates in Paleolithic archaeology has centered on the existence or non-existence of the Movius line, a line dividing two contentiously distinct technocomplex: western Acheulean tool kits and contemporaneous tool kits in the southern and southeastern Asia (Lycett and Norton, 2010). When you compare the mean refinement from this study with data sets from the western and eastern Acheulean, the experimentally reproduced hand-axes are more similar to western as opposed to eastern Acheulean hand-axes (Lycett and Norton, 2010). These results lend credence to the hypothesis that the differences between artefacts from east and west of the Movius line derive from limitations on social transmission in the eastern Acheulean. In other words, hominins east of the Movius line may not have had the same ócognitive tool kitô available to them, whether that consisted of a particular set of social learning capacities, linguistic capabilities or both (as opposed to or in addition to demographic differences, as has been previously suggested).

However, there remains a major obstacle in the way of these interpretations; this comparison is founded on only one or two variables; given more variables for comparison, it could just as likely be that this conclusion is unsatisfactory. One such descriptive variable would be the presence or absence of platform preparation (a technique to which debitage evidence might allude), which can be used as an indicator of expertise (Stout et al., 2014). If evidence of soft hammer percussion from Konso could be confirmed (Beyene et al., 2013), it would suggest that skill acquisition in the early Acheulean may have required different social learning conditions than those experienced by the subject in this study. In addition, the scope of the sample from the Beyene study (one area in Eastern Africa) makes it difficult to make conclusions about temporal change in cognition throughout a geographically expansive technological complex.

Reflections for Future Research

In order to evaluate the hypothesis that the advance from the Oldowan industry to the Acheulean technological complex hinged on cognitive differences, particularly differences in the mode of learning and social transmission, acquisition of Acheulean tool-making skills should be investigated in a larger-scale experiment. One of the most important changes from previous research is to lengthen the learning period that is recorded during the study (as previously mentioned, the duration of previous studies was shorter than would be necessary to properly evaluate cognitive capacities of ancient hominins). The learning period would preferably be longer than was recorded in this study, as well (potentially in the range of 100 or more hours).

Instead of subjects being divided between a verbal and a nonverbal group, I would suggest that subjects within the study be separated into four distinct social learning conditions. Similar to the research design of Morgan and colleagues, the first learning condition would be reverse engineering; the subjects would only have access to the artefacts and not to human instructors prior to practice and attempted replication of hand-axe technology. In the second condition, novice knappers would be left in complete isolation during knapping practice. The main ósocialô input would be footage of expert knappers creating hand-axes without verbal instruction; most importantly, there would be no active feedback during the learning period. The third group would experience a more social learning environment, but without any verbal interaction. Knapping practice would take place in the physical vicinity of other novices as well as an expert knapper who is able to, at most, communicate through gestures. The final condition would be the same as the second, except that the expert would be able to provide verbal feedback and would be more active as a teacher, rather than solely as a more emulative learning model. By creating these three subject groups, it should be possible to tease out the role of language (gestural or verbal) in the social learning mechanisms that underlie the Acheulean technological complex.

Eliminating the potential confound of differing size and quality of blanks from which hand-axes were produced (the hand-axes produced in this study did not come from blanks that were of the same or similar dimensions and shape) would benefit the ultimate goal of determining patterns in changes in size and shape of hand-axes (and therefore better trace the learning process involved in Acheulean hand-axe production). As a way of exerting more control over the experimental conditions, porcelain could be used as the knapping material (as opposed to obsidian, as in this study, or flint), since porcelain can be molded to meet pre-determined dimensions and it meets the physical characteristics necessary for fracture mechanics (Khreisheh, Davies and Bradley, 2013). Standardization of blanks would also help elaborate upon differences not only during learning development, but also between individuals and across different groups.

Conclusion

There are many forms of evidence that contribute to how we can conceptualize how human brains and minds changed during the millions of years of hominin evolution. The archaeological record serves as one such form of evidence; the tools of our predecessors are the preserved remnants of their long-lost mental worlds. By replicating these ancient technologies under experimental conditions, we can better understand the cognition of ancestral humans. In this particular study, experimental replication of hand-axes was utilized to unravel the social learning mechanisms and linguistic capabilities of Acheulean tool-makers. This project intended to build upon prior research into the relationship between language and technological advancement by generating hypotheses for future efforts in the field. By analyzing the efforts of a lone individual to master Acheulean knapping technique, this study has revealed potential indicators of skill development (or indicators of a lack of skill development). From the lack of statistical significance for many of the size and shape variables and other ratios, it is inferred that it is difficult to learn how to knap asocial, non-linguistic conditions, though the role of language remains an open question. However, due to the scale of this study, any findings can hardly be considered concrete and final; comparison of multiple individuals across at least 4 different study groups of differing learning environs (reverse engineering, asocial and non-linguistic, social and non-linguistic, and social and linguistic) using the variety of measures prescribed here could potentially unveil key details about the cognitive underpinnings of learning, tool manufacturing, and language in the early Paleolithic.

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