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An experimental approach to the generation of copying error during the manufacture of material culture:
Implications for cultural evolution

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To my family and Paul for their love and support.

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Abstract

Cultural evolutionary models are marked by an increased understanding that sources of variation such as cultural mutations, or copying error, form an integral part in generating population-level patterns of artefactual variation. Despite recognition that the manual manufacturing process is a fundamental component of material culture in the archaeological record, little is known about exactly how factors related to the manual manufacturing process affect rates of copying error, which potentially influence population-level trends. In addition, only a few studies have incorporated the study of shape variation into cultural evolutionary models even though artefactual shape is affected by evolutionary processes. Utilising an empirical framework that combined methods from the 'psychology laboratory' and morphometric shape data, it was shown on the basis of experimentally produced 3D cultural artefacts that a variety of manufacture-related components significantly impact rates of shape variation produced. Individual experiments confirmed hypotheses stating that differences in components of manufacture, such as contrasting manufacturing traditions, social learning mechanisms, economic factors associated with constraints placed on production time and distinct traditions of 'equipment' employed to produce material artefacts, all influence patterns of shape variation at statistically significant levels. The studies conclude that high mutation loads represent a potential cause for the 'disintegration' of shape traditions over repeated bouts of cultural transmission. Where shape traditions matter in the long-term (e.g., in the case of functional tools such as Acheulean handaxes or projectile points) high fidelity transmission mechanisms may become targets of selection processes associated with manual manufacture. A strong implication for cultural evolutionary models is that the study of the evolution of material culture may, therefore, not be fully characterised solely as the study of cultural *transmission*, but that it can be partly re-conceptualised as the study of the 'management' of the continuous production of mutation loads by various populations of artefact producers.

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Chapter 1 – Introduction to the study of variation in the artefactual record

1.1 The study of cultural evolution

The application of evolutionary theory to material culture in recent years has enhanced comprehension of historical processes in the archaeological record, and recent cultural evolutionary models are becoming increasingly adept at unveiling the evolutionary relationships between cultural traits over the course of artefactual lineages (Neiman, 1995; Lyman and O'Brien, 1998; Henrich and McElreath, 2003; O'Brien and Lyman, 2003; Kuhn, 2004; Mesoudi et al., 2004; Shennan, 2008a; Cochrane, 2009; Mesoudi and O'Brien, 2009; Shennan, 2011; Perrault, 2012; Premo, 2012; Lycett and von Cramon-Taubadel, 2015). Cultural evolutionary models have made specific attempts to define the macro- and microevolutionary processes that affect the variation of cultural traits in the archaeological record (e.g., Neiman, 1995; Bettinger and Eerkens, 1999; O'Brien and Lyman, 2003; Mesoudi, 2011). These models specify how historical change in material culture and biology can be studied within one integrative evolutionary framework (Mesoudi, 2011).

One of the key evolutionary aspects underlying the rich cultural diversity in material culture is the principle of cultural transmission (e.g., Boyd and Richerson, 1985; Cavalli-Sforza and Feldman, 1981). The process of cultural transmission is characterised through the social exchange of knowledge, skills and experiences between individuals (Henrich, 2001; Mesoudi et al., 2006b; Eerkens and Lipo, 2007). At the very basic level, cultural evolution relies on the notion that cultural information travels between members of a population, while allowing cultural information to change and diversify in the absence of genetic mechanisms (Richerson and Boyd, 2005; Coward, 2008). Similar to biological evolution, at the heart of cultural evolution is the notion that historical change occurs as a result of three key Darwinian principles (Mesoudi et al., 2004). These principles are that variation exists amongst cultural traits and that some of this variation is heritable by means of social learning mechanisms, and that some, but not all, of these socially acquired variants may be transmitted to the next generation due to the effect of sorting mechanisms (Durham, 1992; Lycett, 2011). On the population level, cultural transmission may act to affect the social exchange of information between individuals within the same generation (horizontal transmission), between generations (oblique transmission), and between related generations (vertical transmission) (e.g., Mace and Holden, 2005; Collard et al., 2006; Cochrane and Lipo, 2010; Currie et al., 2010; Tehrani, 2013; Crema et al., 2014).

With rising awareness that parallels between cultural and biological evolution can be drawn using Darwinian principles (Mesoudi et al., 2004; 2006a; Mesoudi, 2011), evolutionary methods have recently been adapted to reconstruct the historical relationships between different categories of cultural data, such as cultural artefacts, cultural practices, folk tales and languages (Barbrook et al., 1998; Gray and Jordan, 2000; O'Brien et al., 2001; O'Brien and Lyman, 2003; Dunn et al., 2005; Lipo et al., 2006; Mace and Holden, 2005; Mesoudi, 2007; Tehrani, 2013; Richerson and Christiansen, 2013). On the basis of methods borrowed from biological sciences like phylogenetic methods, it could be surmised that artefact culture follows gradual adaptations as depicted by Darwin's principle of 'descent with modification' (Foley, 1987; Durham, 1992; Shennan, 2011). Phylogenetic methods are particularly adept at unveiling the structuring of sets of traits and provide the advantage of distinguishing similarity derived from related (homology) origin via cultural transmission, from similarity associated with unrelated origin (analogy) that is not derived from cultural transmission processes (Lycett, 2009; O'Brien, 2010). A large sample of cultural data sets has become the focus of investigation in recent years in the attempt to unravel the specific details of their evolutionary dynamics over space and time, for example: stone tools (O'Brien et al., 2001; Darwent and O'Brien, 2006; Buchanan and Collard, 2007; Lycett, 2009) weaving techniques (Tehrani and Collard, 2009; Buckley, 2012) and Turkmen carpet designs (Tehrani and Collard, 2002); canoes (Rogers and Ehrlich, 2008; Shennan, 2008b); ceramic decorations (Neiman, 1995; Shennan and Wilkinson, 2001; Cochrane and Lipo, 2010) and basket traditions (Jordan and Shennan, 2003).

Especially in respect to the study of the archaeological record, much of the study of variation has been concerned with the understanding of temporal and spatial patterns of variation (Kroeber, 1916a, 1916b; Kidder, 1917; Kroeber, 1919; Ford, 1938; Roe, 1969; Wynn and Tierson, 1990; Schlanger, 1996; Eerkens, 1997; Ford, 1999; Lyman and O'Brien, 2000; Dawson, 2001; Truncer, 2006; Lycett and Gowlett, 2008). Since variation is one of the aspects that can be measured in cultural artefacts, it represents a vital component in the study of evolutionary processes in the ‘fossilised’ cultural record (Truncer, 2006). As Kroeber stated (1919, p.238) “Manufactured objects offer an approach which no other class of civilizational data presents: they can be accurately and easily measured.” Archaeology is also becoming increasingly adept at developing sophisticated techniques to precisely measure and quantify variation in morphological components of material cultural artefacts, which facilitates a more precise recording of metric and statistical patterns that inform about underlying evolutionary processes (O’Brien and Lyman, 2003; Lyman and O’Brien, 2006; Lycett et al., 2006; Truncer, 2006; Archer and Braun, 2010; Costa, 2010; Buchanan and Collard, 2010a). Variation is therefore an optimal tool to scientifically investigate testable hypotheses about evolutionary processes, such as the presence of sorting and drift processes, in the archaeological record (Lycett and von Cramon-Taubadel, 2015). With the utilisation of evolutionary methods, an understanding of the temporal and spatial patterning of variation is achieved by tracing similarities and differences, which occur as a result of the diversification of cultural data as populations of people, and/or ideas, split and separate into new lineages (O’Brien et al., 2001; Tehrani and Collard, 2002; Collard et al., 2005, 2006; Mace and Holden, 2005; Cochrane and Lipo, 2010; Jordan and O’Neil, 2010; Crema et al., 2014).

1.2 The study of neutral drift processes and their influence on macroscale variation and cultural change

Recently, computational and mathematical models applied to ethnographic data have considered how evolutionary dynamics underlying cultural transmission, such as biased and unbiased transmission mechanisms, account for such variation and trends observed in the archaeological record on the macroevolutionary level (e.g., Neiman, 1995; Shennan and Wilkinson, 2001; Bentley and Shennan, 2003; Bentley et al., 2004; Brantingham and Perrault, 2010; Steele et al., 2010; Kandler and Shennan, 2013). In unbiased transmission, an individual copies other individuals’ behaviours non-preferentially, whereby the behaviour is equally likely obtained from a parent as from another member of the population (Boyd and Richerson, 1985). According to Bentley and Shennan (2003, p. 460), the consequence of unbiased transmission is that “each variant is copied in proportion to its frequency”. In biased transmission, the likelihood of a cultural variant to be passed on (i.e., for a fraction of variation to be inherited) depends on a variety of cultural selection, or ‘sorting’ biases (i.e., model-based biases such as prestige-bias, or frequency biases such as conformity bias where the most common trait is copied). Thus, biased transmission affects frequency distributions differentially compared to unbiased transmission (e.g., Boyd and Richerson, 1985).

In recent years, the importance of understanding drift mechanisms and their influential role in patterning cultural change and variation has become apparent. Neutral drift models have been adapted from population genetics based on the concept that drift mechanisms in cultural and biological evolution are principally analogous (Koerper and Stickel, 1980). Neiman (1995) initially adapted a stochastic model developed to investigate random drift in genetics to the archaeological record of decorations of Illinois ceramic assemblages from the Woodland period. He demonstrated that drift alone can create cultural change and chronological historical patterns on the basis of incremental small-scale modifications over time. One of the essential implications from stochastic models is that through the introduction and increase of neutral innovations (i.e., copying error), drift can ultimately cause evolutionary change in the absence of biased transmission, especially when different population sizes are accounted for (Neiman, 1995). Recent advances promote the idea that stochastic models might be best employed as null models with one predominant goal: to distinguish random selection from alternative biased selection processes on the basis of differentiating patterns of variation (Neiman, 1995; Shennan and Wilkinson, 2001; Bentley and Shennan, 2003; Bentley et al., 2004; Kohler et al., 2004; Lycett, 2008; Mesoudi and Lycett, 2009; Brantingham and Perrault, 2010; Shennan, 2011).

Biased transmission is comparable to selection mechanisms that are responsible for the systematic filtering of genes during the genetic transmission process, although in the case of culture they need not always be linked to ‘fitness’ criteria in the traditional biological sense (Richerson and Boyd, 2005). In the cultural equivalent, biased transmission acts predominantly on the basis of a variety of social biases through which certain traits are preferred over others according to a set of properties (Boyd and Richerson, 1985). Social biases can take many forms and are broadly divided into content and context biases (Henrich and McElreath, 2003). Content biases describe circumstances where individuals exhibit selective preference for specific content-related traits, such as ideas or beliefs (Henrich and Boyd, 1998; Henrich and McElreath, 2003). Context biases subdivide into model-based biases and frequency-dependent biases; they share a position that the choice of what individuals copy is defined by taking others as models. In the example of prestige and success biases, for instance, individuals copy prestigious and successful individuals as models (Henrich and Gil-White, 2001). Frequency dependent biases describe those biases, such as conformity, whereby individuals copy the most common trait shared by others in the population (Henrich and Boyd, 1998; Kameda and Nakanashi, 2002; Kohler et al., 2004; Mesoudi, 2008) or nonconformity, where individuals prefer novel traits (Shennan and Wilkinson, 2001).

On the basis of computer simulations it has been demonstrated that frequency distributions of neutral drift can follow a power-law or log-normal distribution (Bentley and Shennan, 2003; Bentley et al., 2004; Mesoudi and Lycett, 2009). Contrary to drift, biased transmission describes a modified trait frequency distribution with deviations from stochastic models as certain traits are selectively preferred or avoided (Bentley and Shennan, 2003; Bentley et al., 2004; Mesoudi and Lycett, 2009). The null model has since received attention in the attempt to understand evolutionary processes such as variation, and to try and separate biased from unbiased transmission in a variety of cultural data sets (Bentley et al., 2004, 2007; Mesoudi and Lycett, 2009; Kempe et al., 2012; Brantingham and Perrault, 2010; Kandler and Shennan, 2013; Acerbi and Bentley, 2014). Shennan and Wilkinson (2001), for example, illustrated that variation in Neolithic pottery decorations did not always fit variation levels of drift but fitted variation patterns most complementary to an anti-conformity bias (anti-conformity is expressed through a bias towards the preference for novelty) (Shennan and Wilkinson, 2001). Kohler et al. (2004) compared variation levels in Mexican vessel technology and discovered that a conformity bias (the most common trait is copied) was responsible for a relative lower variation than accountable by drift.

Importantly, this work has also begun to expand to the specific processes that structure variation on the micro-evolutionary level (Bettinger and Eerkens, 1999; Eerkens and Lipo, 2007). The relationship between biased and unbiased cultural transmission in material culture as a tool to understanding cultural variation and change in the artefactual record has, however, still received little attention to date in respect to the microevolutionary processes underlying such population-level changes observed in archaeological data. A few approaches to biased transmission have shed light on the importance of how an understanding of social biases acting on the level of the individual manufacturer forms an essential component of the evolutionary framework of material culture (Henrich, 2001). Bettinger and Eerkens (1999) illustrate how the study of individual-level social biases in the archaeological record can explain patterns of variation in morphological attributes in cultural artefacts on the population-level. They attributed a poor morphological correlation between Great Basin projectile point attributes, manufactured in eastern California to a social bias called *guided variation*. Guided variation is a social bias where individuals copy cultural variants from a variety of other individuals but adjust individual variants additionally with trial-and-error modifications; the compositional nature of this form of copying explains the low similarity between artefacts attributes. Alternatively, Bettinger and Eerkens (1999) described the high morphological correlation between attributes of point artefacts in central Nevada to be the result of an *indirect bias*. Indirect bias is characterised by individuals copying one successful model's complete design; the conditions for high-fidelity transmission as enabled by the indirect bias explains why this form of bias transmission creates such strong correlations between attributes.

Bettinger and Eerkens' (1999) study illustrates two important points in relation to the necessity to study variation more specifically in relation to material culture. Firstly, the strong influence of biased cultural transmission on design adaptations that take effect on the level of the population was demonstrated using explicit archaeological examples (see also Mesoudi and O'Brien, 2008a, 2008b). Therefore, the study draws attention to the importance of understanding the causes of patterns of cultural change in the archaeological record on the basis of specific cultural transmission mechanisms that act on the level of the individual (Eerkens and Lipo, 2007). Secondly, it highlights the importance of microevolutionary mechanisms that can be linked to the macroscale changes and patterns of variation in the archaeological record. In other words, it seems that more investigation is desirable to truly bridge how microevolutionary processes shape macro-level patterns (Baum et al., 2004; Mesoudi and O'Brien, 2009; Shennan, 2011).

1.3 A lesson from biology? Darwin's ignorance of the causes of variation

Mesoudi et al. (2004, 2006a) and Mesoudi (2011) have outlined how the Darwinian principles of evolution as laid out in the *Origin of Species* (Darwin, 1958) are directly applicable to the study of culture. Some of the key evolutionary processes that have not, however, received much attention to date are the causes underlying variation. The above mentioned studies illustrate that a great deal of investigation has been conducted on the macroevolutionary level that explicate how cultural transmission processes shape variation (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985) utilising a wealth of techniques and methods (Neiman, 1995; Jordan and Shennan, 2003; O'Brien and Lyman, 2003; Tehrani, 2013). Yet, Eerkens et al. (2005) recognised the lack of understanding in regards to the microevolutionary processes that shape variation on the macro-scale level in the archaeological record: "understanding of the processes that produce broad-scale changes are still a mystery".

This is perhaps a somewhat similar situation to the very earliest decades of post-*Origin* biology. Indeed, it was Darwin himself who admitted his ignorance in regards to the underlying processes that shape the continuous occurrence of variation in lineages of biological species. In the *Origin of Species*, Darwin (1859, p.37) made a determined attempt to identify at great extent the variation present in the 'characteristics' between individuals of the same biological species, where he defined variation as "many slight differences which may be called individual differences, such as are known frequently to appear in the offspring from the same parents, or which may be presumed to have arisen, from being frequently observed in the individuals of the same species inhabiting the same confined locality". Yet, Darwin knowingly declared his own ignorance of the 'causes' of this variation (Darwin, 1859, p.131).

Knowledge that more specifically defined such causes of new variation was only later established through genetic research. In particular, one source of new variation was identified as genetic 'mutations'. Mutations are changes in character states between individual specimens and have been investigated on the basis of experimental research on *Drosophila melanogaster* (Morgan, 1932; Simpson, 1953; Dobzhansky, 1957; Greenspan, 2004). In the biological sciences, genetic mutations are defined as changes to the genetic material in the form of random copying errors (e.g., via insertion, deletion or substitution of DNA in base arrangements) that can lead to the emergence of a new traits and are the ultimate source of new variation (Kimura, 1968). When considering the cultural analogy, random copying errors can also be defined as forms of 'cultural mutations' that generate altered cultural variants in the course of transmission and are specifically associated with the generation of *new* variation (Simpson, 1953; Mesoudi et al., 2013). In that respect, errors in the copying process can be described as “loosely analogous to random mutation in genetic evolution” (Mesoudi et al., 2013, p. 199). Yet, despite Darwin’s self-declared ignorance regarding the causes of variation, the *Origin of Species* proposed the ultimate foundation for the evolutionary theory, in both biology and culture (Mesoudi et al., 2004, 2006a), determining that variation is ultimately required for selection mechanisms to act upon, such that some of that variation is ‘inherited’ by following generations. Ultimately, for the evolutionary process, or descent with modification, to persist, the presence of new variation is a key mechanism, as otherwise selection mechanisms cannot operate (Provine, 1971). Furthermore, Mesoudi (2006a) stressed the necessity for the cross-disciplinary synthesis of method and theory in order to advance the study of Darwinian evolutionary approaches that can be utilised to further study mechanisms of change, variation and diversification in the archaeological record. Such a synthesised evolutionary approach may be necessary to uncover further how microevolutionary mechanisms like mutations can bring potential effects on variation and change on the macroevolutionary level.

1.3.1 The study of sources of new variation in material culture

In particular respect of the study how variation is created in material cultural artefacts, different causes of variation have been discussed in recent years. ‘Innovations’, which in the most general and simple of terms, might be regarded as cultural variants that are deemed novel (O’Brien and Shennan, 2010; Shennan, 2014), and are often viewed as analogies to genetic mutations (Cavalli-Sforza and Feldman, 1981). Recently, Mesoudi et al. (2013, p.197-198) expanded the concept of what constitutes sources of variation by explaining that innovations may enter the archaeological record by a variety of means, for example, through principles of recombination and exaptation. Boyd et al. (2013) illustrate an example of how new variation in material artefacts can be introduced through the principle of ‘recombination’, for example, where novel tools can be created by the combination of two existing elements, each a component of separate tool traditions, in the absence of any newly generated innovations “an Inuit might copy the bow design from the best bowyer in his community but adopt the sinew plaiting used by the best hunter in a neighbouring community. The result could be a better bow than anyone made in the previous generations without anyone inventing anything new”.

However, in recent years the concept that copying errors (i.e., cultural mutations) are a valuable source of continuous neutral variation in metric attributes of material culture has been explored more specifically in empirical and computer modelling research (Eerkens, 2000; Eerkens and Lipo, 2005; Hamilton and Buchanan, 2009; Kempe et al., 2012; Gandon et al., 2013, 2014). Eerkens and Bettinger (2001) formulated technical models of variation in relation to microscale copying errors. Similar to population-level drift models, they have focused on extending concepts of drift as a null model to the study of copying errors that become introduced during the making of artefacts.

One prominent example by Eerkens and Lipo (2005) elaborated to what extent causes of variation on the small-scale can generate effects that can create detectable levels of variation on the macro-scale level. Their study was concerned with how variation is linked to copying errors that arise as a result of human perceptive limitations. One of the sources of variation to contribute to stochastic error in manual manufacture is the human perceptive limitation to detect variation below ~3% difference in size estimation between two objects produced to be of equivalent size. This ~3% threshold beyond which variation is deemed imperceptible has been termed the ‘Weber Fraction’ (Eerkens and Bettinger, 2001). Therefore, if two similar objects contain variation in size below ~3%, human perception would fail to detect this variation and these objects would be perceived as equivalent. This means that the manufacturer of a cultural artefact will inescapably produce copying error below the ~3% threshold. This is relevant for the manual manufacture of cultural artefacts as these undetectable levels of variation enter the archaeological record and are transmitted to other generations, potentially generating change in the long-term. In order to test how such copying error becomes introduced as a result of these human perceptual limitations and affects variation in the long-term, Eerkens and Lipo (2005) modelled the unbiased transmission of selectively neutral attributes associated with “length of an arrowhead” over the transmission of 400 generations (with 10 individuals in each generation) in separate cultural transmission chains. Cultural transmission chains are characteristic for the passing of social information between individuals in a chain-like fashion reminiscent of ‘Chinese Whispers’ or ‘Broken Telephone’ games (Horner et al., 2006; Mesoudi and Whiten, 2008; Caldwell and Millen, 2008; Muthukrishna et al., 2013).

Eerkens and Lipo’s (2005) computer model (also later termed as the “accumulated copying error model” or “ACE” model by Hamilton and Buchanan (2009)) showed that copy error produced because of this perceptual limitation accumulated in a stochastic fashion over time. Specifically, over the repeated course of inter-generational transmission of size attributes, copying errors accumulated in a fashion such that individual transmission chains became smaller while others would become larger. This divergence meant that between-chain variation increased over time even though mean size values did not change. The model highlighted that compounded copying error, accumulated over multiple inter-generational transmission events, contains the potential to ultimately generate macro-scale level trends and change.

Eerkens and Lipo (2005) also applied the model to understand how social biases affected stochastic copying error. In a further simulation, Eerkens and Lipo (2005) tested the effects of conformity bias (copying the average value) and prestige-biased transmission (copying a selected individual) on the copy error rates. Since the model illustrated that both prestige and conformity reduced variation compared to stochastic drift, their research largely complements other computational models that investigated cultural change in frequency distributions of cultural attributes to understand deviations in the patterns of variation under the influence of biased versus unbiased cultural transmission (e.g., Neiman, 1995; Shennan and Wilkinson, 2001; Bentley et al., 2004; Steele et al., 2010; Kandler and Shennan, 2013). When applied to archaeological data in terms of 100 Rose Spring projectile points, Eerkens and Lipo’s (2005) model showed that the basal width obtained from Owen Valley contained less variation compared to patterns of copying error assumed to be under neutral random processes, and according to their simulation, patterns of variation were under the influence of selection and most compatible with a conformity bias. Conversely, thickness measures described a pattern more in accordance with random neutral variation, thus, thickness attributes of Rose Spring points were mostly changing according to drift processes.

Other efforts extend such findings, illustrating that random neutral rates of copying error can accumulate and generate visible trends in artefacts such as Clovis projectile points (Hamilton and Buchanan, 2009). However, Lipo and Eerkens’ (2005) study was one of the first to hint towards the fundamental importance of understanding the distinct ‘causes’ of such variation upon which evolution (i.e., selection and drift) act upon because the continuous cultural transmission of copying error can compound and generate detectable levels of variation and substantial change over time. Importantly, the model by Lipo and Eerkens (2005) also highlights that the study of copying error (i.e., the study of small-scale variation in continuous cultural attributes) has powerful explanatory value in the understanding of underlying causes of variation that have the potential to generate effects on the macroevolutionary level. In that respect, small cultural mutations that enter the archaeological record can have important ramifications for trends and changes on the level of the population. Recently, a computational agent-based model by Rorabaugh (2014) also extended on the findings of the ACE model in regards to the effects that demographic factors can have on copying error. The computational model manipulated the increase and decrease (i.e., evolutionary bottlenecks) of effective population size on copying error and therefore extended the utility of the study of causes of variations to wider use of evolutionary models such as those concerned with the effects of population size, migration and population density on the social conditions and level of cultural transmission required to sustain complex technologies (Henrich, 2004; Lycett, 2007a; Lycett and von Cramon-Taubadel, 2008; Powell et al., 2009; Ross et al., 2013). Moreover, such studies emphasise that the study of copying error can be utilised in the empirical investigation of testable hypotheses in regards to factors that underlie patterns and causes of variation in material culture.

1.3.2 Experimental advances in the study of variation in material culture

Experimental simulation studies of cultural transmission in a laboratory setting have only very recently gained great focus within a range of research disciplines of cultural evolution. Experimental advances have also been used to study evolutionary processes associated with language transmission (Kirby et al., 2008), bird songs (Fitch, 2009) communication (Tan and Fay, 2011), social information (Mesoudi et al., 2006b) and cultural artefacts (Mesoudi and O’Brien, 2008a; Kempe et al., 2012). In addition, experimental models have been applied to the study of cultural behaviours in human adults (Schotter and Sopher, 2003; Mesoudi and Whiten, 2008), human children (Flynn and Whiten, 2008) and non-human primates, such as chimpanzees (e.g., Horner et al, 2006; Whiten and Mesoudi, 2008). Cultural transmission experiments, for example, are simulation models specialised to trace evolutionary processes during inter-generational transmission events. Intergenerational transfer of information is facilitated by the transfer of social information along linear sequences of participants (Bartlett, 1932;

Jacobs and Campbell, 1961; Mesoudi and Whiten, 2008, Kempe et al., 2012). One of the advantages of experimental studies is that resulting patterns and trends can provide potential insights into the cultural trends in the archaeological record (Mesoudi, 2007; Mesoudi and Whiten, 2008). In addition, a key advantage of experiments is the ability to monitor the constant modification and introduction of microscale changes on the level of the individuals; this makes experimental endeavours optimal tools for the study of microevolutionary events (McElreath et al., 2005).

Yet to date, very few experimental studies have focused on the effects of factors that affect variation or sources of variation, in material artefact evolution *per se* (Eerkens, 2000; Kempe et al., 2012; Gandon et al., 2014). While material artefacts have been utilised within experimental models of cultural evolution, they were primarily employed as tools for investigation of the social and psychological mechanisms involved in learning and transmission of cultural variants. For example, Caldwell and Millen's (2008) research involved the inclusion of 3D material artefacts, such as paper aeroplanes and spaghetti towers, to experimentally study simulated evolutionary processes such as cumulative cultural evolution and convergence in the laboratory. Similarly, Muthukrishna et al. (2013) and Kempe and Mesoudi (2014) explored the demographic conditions necessary for cumulative cultural evolution within an experimental context, illustrating that multiple models (increased population size) is a crucial prerequisite for cumulative modifications in material culture. In addition, Caldwell and Millen (2009), Caldwell et al. (2012) and Wasielewski (2014) explored the social learning mechanisms required for cumulative cultural evolution to persist, utilising 3D cultural artefacts. Despite increasing awareness of the appropriateness of applying evolutionary processes by studying cultural transmission processes experimentally, the absence of such experimental approaches in relation to the study of evolutionary processes in material culture and the archaeological record is still apparent (Mesoudi and O'Brien, 2009). In addition, while numerous approaches in the field of experimental archaeology have been directed toward the study of material artefacts, especially in regards to prehistoric stone tool technology, focus has largely been placed on physical properties, performance-related aspects and the inference regarding past human cognitive and behavioural components (e.g., Ascher, 1961; Newcomer, 1971; Jones, 1980; Machin et al., 2007; Stout et al., 2008; Wilkins et al., 2012). In sum, little focus has been placed on furthering theoretical and scientific approaches to the study of evolutionary processes underlying artefactual culture on the basis of relevant experimental simulation models that could complement recent endeavours to the study of factors that generate patterns and trends of variation (Eerkens, 2000; Eerkens and Lipo, 2005).

However, rare examples have attempted to study the effects of evolutionary mechanisms on material culture more specifically. One of the few attempts to specifically undertake empirical research to enhance the understanding of evolutionary processes underlying artefactual data is Mesoudi and O'Brien's (2008a) experimental simulation which is grounded in Bettinger and Eerkens' (1999) ethnographically-based study that investigated the effects of different social biases on projectile point morphology. Mesoudi and O'Brien (2008a) experimentally investigated the production of projectile points by simulating the effect of social transmission biases such as indirect bias, against a further hypothetical possibility, that of guided variation which contains higher levels of individual learning (i.e., trial-and-error learning). In their experiment, participants generated virtual arrowheads with the opportunity to alter morphological attributes, such as length, width and depth. The morphological attributes were associated with different hunting success rates. Hunting success depended on a variety of continuous length, width and thickness attributes plus discrete shape features. Also, while colour options were also provided, colour variation was irrelevant for hunting success. In one experimental condition, participants were asked to copy previous players' successful designs; this condition was, therefore, associated with an indirect bias. In another experimental condition which simulated guided variation, participants could modify the morphological attributes but could not copy others' designs. The investigation strengthened Bettinger and Eerkens' (1999) initial explanation that morphological changes were, in fact, attributable to social transmission biases. Thus, copying the most successful individual (i.e., indirect bias) was also attributed to higher correlation of morphological features, compared to those morphological correlations resultant from individual learning (guided variation). Also, social learning (e.g., via horizontal transmission) reduced within-group variation, compared to individual learning, and generated higher performance rates which led to social learning outperforming individual learning (i.e., guided variation).

However, Mesoudi and O’Brien’s (2008a) experimental investigation also facilitated a more refined understanding of how exactly the different cultural transmission processes shape diversity and variation in the archaeological record. Their experimental endeavour came to the conclusion that Bettinger and Eerkens’ (1999) findings were best supported by the notion that different morphological combinations were associated with various optimal adaptive fitness peaks (i.e., the adaptive landscape may contain multiple optimal and suboptimal fitness values associated with different arrowhead designs, as opposed to just one optimal design or unimodal fitness landscape). Guided variation allows individuals to experiment with different designs but eventually the manufacturers would settle on different fitness peaks, without being able to ‘jump’ to higher fitness peaks. Conversely, the enhanced ability for social learning associated with the indirect bias facilitated the jumping from assemblages associated with lower fitness peaks to those associated with some of the more optimal or higher fitness peaks (Mesoudi and O’Brien, 2008a). The study emphasises that archaeological approaches benefit from experimental investigations. This is because experimental endeavours can yield additional insights into evolutionary processes that structure variation in the archaeological record.

Similar to the investigation of social transmission biases in the archaeological record, the study of the production of copying error within an explicitly experimental context has been largely under-represented. A rare exception of the study of copying error within an experimental context is a study conducted by Eerkens (2000) who tested the impact of memory limitations on the production of rates of copying error in 2D artefact shapes. As part of a simple experimental model, participants copied the shape and form of 2D objects like a business card or a US dollar using scissors and paper. In one experimental condition, participants replicated specific target forms from memory alone. In the alternate condition, participants could view target forms before copying these. By statistically comparing differences in error rates produced in the two conditions, the study verified that error rates were higher when participants relied on long-term memory as opposed to viewing the target forms shortly before the manufacturing task. The study is the only one to date that specifically targets the study of copying error in material culture within an experimental context that comprised the manual production of artefacts. Even if the study primarily focused on the study of copying error on the principle use of basic 2D shapes, the experiment highlights the utility and feasibility of simple experimental simulation models for the study of evolutionary processes such as variation in material culture.

A recent study by Kempe et al. (2012) may be mentioned as a further rare example that investigated evolutionary processes in artefactual culture within an experimental context. The study investigated Eerkens and Lipo's (2005) accumulated copying error model in an experimental model to understand whether experimentally-derived data from human participants on sources of copying error matched the findings of Eerkens and Lipo's (2005) purely computer-based model. As part of the experiment, multiple cultural transmission chains were generated where each participant copied the size of a realistically looking Acheulean handaxe image displayed on an iPad from a previous chain member. In this experiment, copying error derived from human perceptual limitations (i.e., Weber fraction) was measured in the 'handaxe length' of the Acheulean images. Kempe et al. (2012) generated 20 cultural transmission chains, each chain containing 10 participants. Each participant was asked to adjust the size of their Acheulean handaxe image to the image from a previous chain member. In one experimental condition, participants resized their image which was set at the maximum length. In the second condition, participants resized their image starting from a smaller scale set at 1/3 of the maximum. The experimental data set supported the original model by Eerkens and Lipo such that over the course of cultural transmission 'mutations' in the form of undetectable copying errors introduced by human perceptual limitations can generate visible changes and variation in the long-term as a result of between-chain variation increasing substantially over time. However, unlike the initial simulation model by Eerkens and Lipo (2005), mean size did not stay the same but actually increased over time in the experimental condition where participants had to increase the size of their image in order to match the target image presented to them. The study thus highlights the value of the experimental investigation of copying error and its introduction in the processes involved in artefactual production to precisely understand evolutionary processes acting on variation in material artefact culture. Kempe et al. (2012) also showed that unbiased copying error can be used as a 'null model' that can be tested against rates of cultural mutations generated by biased, or non-random, forms of transmission. This is in accordance with recent advances which promoted the idea that stochastic models might be best employed as null models to distinguish random from socially biased transmission processes (Neiman, 1995; Bentley and Shennan, 2003; Bentley et al., 2004; Kohler et al., 2004; Lycett, 2008; Mesoudi and Lycett, 2009; Shennan, 2011). In that respect, Kempe et al.'s (2012) analysis of a database of 2601 Acheulean handaxes showed that the handaxes contained less variation compared to the variance levels generated from random unintentional rates of copying error obtained from their experimental model. This illustrates that metric attributes of Acheulean handaxes might be under the influence of biased, non-random, cultural transmission.

The studies by Eerkens (2000), Kempe et al. (2012) and Mesoudi and O'Brien (2008a) highlight that the utilisation of material cultural artefacts in experimental settings is a vital component of the study of evolutionary processes that affect patterns of change. Importantly, Eerkens (2000) and Kempe et al.'s (2012) studies emphasise that the scientific investigation of variation and sources of variation acting on the microevolutionary level via experimental research can be done on the basis of testable theoretical hypotheses and by means of verifiable statistical analyses carried out on metric artefact attributes. In addition, Mesoudi and O'Brien's (2008a) showed that the study on social transmission processes that affect variation and diversity (e.g., Bettinger and Eerkens, 1999) can be specifically investigated on the level of the population within a 'virtual laboratory' setting; e.g., utilising controlled environments and modifiable cultural artefact images like digital arrowheads and 2D Acheulean handaxe images. Such experimental endeavours illustrate the importance of the study of microevolutionary variation, introduced as mutations between individual artefact assemblages, in the attempt to enhance how microevolutionary processes pattern variation on the population level. Despite the overarching lack of experimental endeavours to this date, Mesoudi and O'Brien (2008a, p. 25) illustrate the utility of simple experimental models borrowed from biological sciences to further enhance the understanding of evolutionary processes in the archaeological record: "Simple, highly controlled experimental simulations of biological inheritance and selection have been enormously useful in explicating the complexities of biological evolution, and experimental simulations of cultural transmission can be similarly useful in explicating the complexities of cultural evolution."

1.3.3 Gaps in current research literature in regards to the experimental investigation of sources of variation

Despite isolated efforts from a range of disciplines such as biology, social, cognitive, experimental, comparative psychology and archaeology to deepen our theoretical understanding on the evolutionary mechanisms in material cultural evolution (McElreath et al., 2005; Shennan, 2008a; Mesoudi and O'Brien, 2009; Whiten et al., 2009a; Stout, 2011; Mesoudi, 2011) the underlying processes regarding the sources of variation are still not well studied to date. As Baum et al. (2004) stated: "Perhaps the single most neglected field of empirical investigation in evolutionary social science is the study of the processes of cultural microevolution." In regards to the archaeological record, there has been overarching interest regarding the study of variation that generates differences between assemblages and patterns and trends over the temporal and spatial spectrum (e.g., Roe, 1969; White, 1998). Yet the question of how *microscale* modifications come to explain population-level trends in the ethnographic record remains largely unexplored (Eerkens and Lipo, 2005; Mesoudi and O'Brien, 2008a; Coward, 2008; Gowlett, 2010). Additionally, the specific social learning mechanisms that underlie cultural variation and diversification processes in material culture are still poorly understood in relation to how they affect copying error (Shea, 2009). This is despite recent cultural evolutionary models outlining the explanatory power of social learning in shaping patterns of variation in the archaeological record (e.g., Boyd and Richerson, 1985; Eerkens and Lipo, 1999; Shennan, 2000; Mesoudi and O'Brien, 2008a).

In addition, despite the fact that a few recent empirical advances can be mentioned that attempt to link microscale evolutionary processes of drift and selection to macroscale patterns, such as copying error introduced through perceptual, memory and also motor constraints (Eerkens, 2000; Kempe et al., 2012; Gandon et al., 2013, 2014), empirical investigations on the sources of variation as imperative evolutionary processes of material culture remain rare. Experimental applications in regards to the study of evolutionary mechanisms in culture have, however, been utilised in other areas. While specific evolutionary processes like social biases (Mesoudi and O'Brien, 2008a), economic decision-making (Schotter and Sopher, 2007), drift (Kempe et al., 2012), cultural learning (Caldwell and Millen, 2009; Caldwell et al., 2012; Wasielewski, 2014) and mechanisms of cumulative cultural evolution (e.g., Caldwell and Millen, 2008) as well as demographic factors (Muthukrishna et al., 2013; Derex et al., 2013; Kempe and Mesoudi, 2014) have been the focus of experimental investigation, little has been done to date to study evolutionary processes in specific respect to how variation is differentially *generated* in material culture within a specific experimental context (Eerkens, 2000; Kempe et al., 2012). The importance for the further study of the effects of cultural mutations on the macroscale is best illuminated by Eerkens and Lipo (2005), Hamilton and Buchanan (2009) and Kempe et al. (2012) who demonstrated empirically and ethnographically that the effects of accumulating random microscale changes as a result of error can be strong enough to generate macroscale changes in artefact designs over the course of intergenerational cultural transmission. Given the importance that cultural mutation can harbour variation and detectable level of change over the long-term (e.g., Eerkens and Lipo, 2005), a more complete understanding of the cultural evolution in the artefactual record requires an inclusion of more detailed empirical knowledge of the factors that source variation on the microscale processes in order to better understand population-level changes, variation and diversification (Shennan, 2011).

In addition, despite the determined effort to understand how random drift as opposed to other non-random cultural transmission events pattern trends of variation (Neiman, 1995; Shennan and Wilkinson, 2001; Bentley et al., 2004; Eerkens and Lipo, 2005), to date little is understood about copying error as a variation-generating factor during the *manual manufacturing proces*s of cultural artefacts. Gandon et al. (2013, 2014) recently studied the introduction of copying error specifically during the production of three-dimensional pottery artefacts and illustrated that culture-specific learning of motor skills (that may be shared among one population but not another) is associated with distinct traditions of manual manufacture. Importantly, such traditions of motor skills (that may be shared by one population but vary between populations) have been demonstrated to be a predictor of culture-specific patterns of metric variation. These findings ultimately highlight the fact that more studies need to address this important facet of material culture. Unlike other forms of culture, such as language, religion, and other forms of cultural practices and social behaviours, material culture is idiosyncratic in the fact that it needs to be *physically* manufactured. Yet, the production process of material culture has been largely neglected in evolutionary models despite the fact that the manufacture is an inevitable and prominent component of all material culture, and potentially harbours variation in the form of cultural mutations. For example, despite all these possibilities for culturally acquired differences that potentially underlie variation and divergence in artefact lineages (Bettinger and Eerkens, 1999; Mesoudi and O’Brien, 2008a; Gandon et al., 2013, 2014), there are no experimental models to date that specifically investigate the effects of distinct manufacturing processes on patterns of variation.

In that respect, the state of current material culture study involving evolutionary theory contains certain shortcomings. First of all, studies tend to focus on the study of macroscale processes while little has been done to investigate the evolutionary microscale changes as a result of copying error that give rise to the macroscale processes as described above (Bettinger and Eerkens, 1999; Baum et al., 2004; Eerkens and Lipo, 2005; Eerkens and Lipo, 2007; Tehrani and Collard, 2009; Shennan, 2011). Second, there is largely an absence of the experimental investigation of microevolutionary mechanisms that incorporates the manual production of physical artefacts within a laboratory context that may help shed light on how the manufacturing process sources copying error at statistical levels.

1.4 Thinking further about experimental approaches to the study of evolutionary processes in the archaeological record

The study of artefact culture would therefore benefit from an experimental approach to test specific hypotheses based on the individual processes that give rise to cultural variation and those social processes that affect patterns of variation (Eerkens and Lipo, 2005; McElreath et al., 2005; Mesoudi and Whiten, 2008; Mesoudi and O’Brien, 2009). Experimental simulation studies allow for the detailed observation and recording of the transmission of social information passed between groups of participants. Unlike the experimental context, the archaeological record is deprived of any direct means of observation or knowledge on the explicit social context (Binford, 1983). As Eerkens and Bettinger (2001) have stated, the observation of social processes of specific interest to the evolutionary archaeologist is difficult on the basis of archaeological data and methods alone.

In many ways, experiments yield complementary insights to ethnographic approaches (Mesoudi, 2011). To give only a few examples of the scientific advantages, experimental research benefits from exerting greater control over environmental, social and demographic processes in favour of investigating isolated factors and processes than is possible in an ethnographic context (McElreath et al., 2005). The advantage of experiments for studying microevolutionary processes is particularly relevant for an enhanced understanding of closer investigations of sources of variations, like mutations, that are produced on the level of the individual, and their effects on the archaeological record which would be challenging to achieve solely on the basis of ethnographic data. For example, Mesoudi and Whiten (2008) as well as Laland (2004) conceptualize the benefits of experiments in a way that these allow for the precise monitoring of microevolutionary events such as *what* information is copied, *who* is taken as a model, and the reasons *why* specific cultural traits are acquired.

In 1932, Thomas Hunt Morgan, a pioneer for his research on mutation and heredity in *Drosophila melanogaster*, pointed towards the optimality of laboratory experimental investigations for the specific study of mutations and other microevolutionary mechanisms affecting variation and heredity. He argued for the advantage of experimentally based research to produce verifiable conclusions derived from the testing of theoretical statements which are based on controlled experimental data as opposed to descriptive broader generalised observation (Morgan, 1932). As Morgan states (1932, p. 14), “it is now realized that the most promising model for the interpretation of evolution is through an appeal to experiment. By an appeal to experiment is meant the application of the same kind of procedure that has long been recognized in the physical sciences as the most dependable one in formulating an interpretation of the outer world.” Conversely, there is little control over the study of isolated microevolutionary processes in the ethnographic record in a fashion that can be achieved in the laboratory context. Ethnographic data are also disadvantaged insofar that people cannot be randomly assigned to specific conditions in order to achieve higher homogeneity between populations of interest, for example (e.g., Gandon et al., 2013, 2014). Experiments also allow for the structured study of microscale processes and their context; historical processes can be investigated closely and ‘rerun’ whereby gaps in ethnographic data sets can be addressed and specific statistical effects repeatedly verified (Mesoudi and O’Brien, 2009). Thus, the experimental study of metric variation allows for the monitoring of detailed observable events (Mesoudi and O’Brien, 2009). In this respect, experiments provide the ability to test specific ideas empirically and provide fundamental knowledge of specific processes that would be otherwise difficult to investigate. In addition, experiments provide the ideal context to investigate the effects of past human social behaviours (i.e., social learning) that are hypothesised to underlie effects on artefact culture but are difficult to investigate from the utilisation of purely archaeological methods.

In that respect, ethnographic data have little “internal validity” such that it is difficult to exert control over a variety of confounding factors to truly understand the causal nature of isolated factors by means of manipulation of specific components (Mesoudi, 2011). Given the characteristics of experiments to investigate microevolutionary processes in a controlled manner, experiments are therefore optimally suited for the simulation of mechanisms concerned with the production of variation like copying error within a laboratory context (Kempe et al., 2012). Bataillon (2013, p. 2), urges that the value in experimental investigations lies in the “capacity to test quantitative assumptions and predictions that do not yield easily to comparative and retrospective analyses of natural populations.”

Experiments have certain short-comings as well. When compared to ethnographic studies, experimental approaches offer high “internal validity” but cannot reach the level of “external validity” as those of ethnographic research (Mesoudi, 2011). When studying material culture, ethnographic studies have high “external validity” given that their research approach is based on the wealth of real-world artefacts, potentially collected over large geographical areas and differing socio-economic settings. This allows for the investigation of different environment and demographic factors and their influence on artefact change. Unlike most experiments, ethnographic recordings allow for the tracking of cultural developments over extended time periods. Recently, Gandon et al (2014) illustrated how different traditions of culturally acquired motor skills for pottery artefact making in different ethnic groups (India versus France) can impact on how copying error is produced in different metric attributes of similar shapes of pottery artefacts. Such ethnographically-based investigations give an impression of real cultural behaviours present in different geographical regions in a fashion artificially produced cultures in the laboratory cannot. In addition, because of the difficulties regarding feasibility and cost-related issues involved in the investigation of large quantities of participants in the laboratory over the long-term, experiments are relatively constrained in testing realistically large sample populations over extended periods of time (i.e., decades or even centuries).

To some extent, some of the short-comings from experimental research might be addressed by complementary computer-based experiments, also termed ‘the virtual laboratory’, in respect to artefact evolution (Mesoudi and O’Brien, 2008a; Kempe et al., 2012; Derex et al., 2013). Virtual game situations have been undertaken in respect to social learning as an adaptation strategy (Kameda and Nakanishi, 2002; Rendell et al., 2011). Computer-based experiments coupled with simulations work have pronounced advantages, such as the simulation of consequences of evolutionary trends over thousands of generations based on experimental results that were obtained under controlled laboratory conditions. In addition, a virtual game environment can make use of shared computer interfaces that generate ideal conditions to study social and demographic effects within a ‘virtual laboratory’ context with relative ease (Mesoudi and O’Brien, 2008a). Recently, for example, Derex et al. (2013) investigated demographic effects in respect to cultural evolution and illustrated that decrease in group size lead to maladaptive loss of existing technological complexity (Henrich, 2004) in arrowheads and fishing nets.

However, despite certain shortcomings, experimental approaches have the overarching advantage that they facilitate study of tactile and physical factors in a fashion impossible by utilising the ‘virtual laboratory’. Moreover, experiments can study isolated components (i.e., learning context, tool utilised for production and other forms of manufacture-related tradition) that may play a fundamental role in the production of copying error and variation in a fashion not previously explored, and impossible to discover by purely archaeological means. Therefore, while archaeologists cannot directly obtain observable information on how information regarding the manufacturing process is passed between group members via social learning mechanisms, experiments facilitate the simulation of the social behaviours and factors that play a role in the formation of empirically measureable data. Therefore, experiments are in some respect complementary to both computational and archaeological approaches such that they can realistically address the interaction between evolutionary processes and the effects of *physical* and *tactile* properties of the manufacturing process on variation. Similarly to the virtual laboratory, experiments retain a high level of control over environmental impacts so that factors of interest can be manipulated. Such an approach to the study of cultural evolution in regards to material culture would uniquely benefit the enhanced understanding of variation in the archaeological record; linking and innovatively combining advantages of different and interdisciplinary methods has been associated with the benefit of a "fuller account of past cultural evolution" (Mesoudi and O'Brien, 2009, p. 21).

1.5 Relevant questions regarding the factors that source copying error in the manual manufacturing process

Questions regarding how differences in the manual manufacturing process may affect the generation of variation have long existed among archaeologist (Foster, 1960; Arnold, 1991; Arnold and Nieves, 1992; Stout et al., 2014). Arnold (1991) noted anecdotally that different manufacturing traditions applied to pottery production substantially differ in respect to how between-assemblage variation is generated. Similarly, Gandon et al. (2014) noted that within-assemblage patterns of variation vary according to culture-specific manufacturing techniques (i.e., different populations utilising distinct manufacturing traditions in pottery manufacture generate distinct patterns of variation). Thus, while the manufacturing process has received some association with the generation of variation, a lot of questions regarding how exactly variation, or cultural mutations, become introduced, remain unattended by experimental methods to date. Yet, there are questions that are grounded in testable hypotheses and contain potential implications for the archaeological record.

For example, the question how variation is affected by the manual manufacturing process may be particularly relevant where manufacturing processes are fundamentally different. This has been noted by Deetz (1967) who hypothesised that profoundly diverse manufacturing processes may have distinct impacts on patterns of variation. Two predominant manufacturing processes that exist in the archaeological record are irreversible, or 'reductive' manufacturing techniques that are employed specifically in the production of stone tool artefacts via knapping processes, and reversible manufacturing processes involved in the manufacture of material culture such as pottery or basketry, for example. Irreversible manufacturing traditions like stone knapping have the specific characteristic that material can be removed; however, material that has already been removed from the 'core' cannot be added. Conversely, reversible manufacturing traditions, like pottery production, have the characteristic that material can be both added and removed during the manufacturing process. Thus, error can be reversed by adding or removing material in the reversible production process, whereas irreversible production processes can only address errors by additional material removal. According to Deetz (1967), this generates a higher potential for irreversible manufacturing processes to generate higher levels of variation, compared to reversible processes. Yet, due to lack of empirical verification of how microevolutionary processes like cultural mutations are introduced during the manual manufacturing process, this theoretical concept has not been investigated empirically to date despite general consensus that that the manufacturing process matters in the production of artefactual variation (Deetz, 1967; Foster, 1960) .

Another factor that is ultimately linked with the production of artefactual culture is the time invested into producing material culture. Torrence (1983) stressed how time investment in the production of artefacts is an important component but also a ‘costly’ economic factor because the production time invested into the manufacture of cultural hunting artefacts competes with other important survival-enhancing subsistence activities (see also Binford, 1978, 1979). Given the pervasiveness of ‘constraints’ placed on the production time involved in the manual production of artefacts, it is essential to understand exactly how varying levels of time constraints affect copying error.

In addition, it is unknown how the impact of other factors related to the manual production of material culture, such as differences in the traditions of tools or equipment employed in the manual manufacture of cultural artefacts, affects copying error in material cultural artefacts. This is despite extensive records of different tool traditions employed in the production of same types of artefacts, such as ‘hard’ stone versus ‘soft’ antler hammers in stone tool production, for example (e.g., Driscoll and García-Rojas, 2014; Stout et al., 2014). Other variants of multiple different techniques employed are known to the production of pottery artefacts, for example, hand-made pottery as opposed to wheel-throwing techniques, for example (e.g., Arnold, 1991; Courty and Roux, 1995; Lindahl and Pikirayi, 2010; Roux, 2010). However, there is no experimentally controlled knowledge in regards to how different traditions of the equipment employed in production processes might generate effects on metric copying error despite anecdotal measurements alluding to the possibility that manufacturing tools have impacts on the variation generated (e.g., Arnold, 1991). These examples strengthen the importance to specifically investigate the specific physical and tactile factors related to the manual production of material artefacts to enhance our understanding of how variation that generates long-term diversification and change, initially enters the archaeological record. Thus, these components of manufacture, which potentially affect long-term variation and change, call for the empirical investigation of the specific microevolutionary factors that generate variation in artefactual culture. There are, inevitably, a variety of tactile, physical, economic and social factors that are integral elements of the production process and can potentially affect the rate of copying error produced. Hence, this thesis focuses on the investigation of some of these specific components that have the power to specifically answer questions regarding the precise sources of variation that the manufacturing process can harbour.

1.5.1 The question how social learning affects artefactual variation and the generation of long-term cultural traditions

Social learning is the capability to learn behaviours, skills and ideas by observing others or the outcomes of their behaviour, and changing and adapting subsequent behaviours correspondingly (Laland, 2004; Allen et al., 2013; de Waal, 2013). Social learning has been studied extensively throughout the animal kingdom because it yields a strong functional and explanatory role in the variation of behaviours and social traditions existent in human and non-human primate species (van Schaik et al., 2003; Whiten et al., 2004; Whiten and Mesoudi, 2008), specifically chimpanzees ((McGrew, 2004; Whiten et al., 2005; Lycett et al., 2007; Galef, 2012; Hobaiter et al., 2014; Fuhrman et al., 2014)) or other non-human animal species, for example, such as fish (Brown and Laland, 2003) and meerkats (Thornton and Raihani, 2010). .

Social learning has been linked to the establishment of cultural variants as traditions shared by other members of the same population, but not necessarily by members of other populations in chimpanzees (*Pan troglodytes*) (Whiten et al., 2005; Horner et al., 2006). Hence, population-specific social transmission events account for within-group convergence and between-group divergence that can explain the vast diversity of social and tool-use behaviours recorded in wild chimpanzees (Whiten et al., 1999; Boesch and

Boesch, 1990; McGrew, 1992; Boesch, 2003; Lycett et al., 2007). Given this, it is not a far stretched implication that social learning processes may have equally mediated stable detectable patterns of variation and diversification which have led to traceable differences in material traditions in early artefactual culture manufactured by our hominin ancestors. However, little has been done to test empirically how different forms of social learning affect copying error.

In a directly related set of literature, social learning has received growing attention in the debate surrounding the specific factors that make human culture 'cumulative' and distinctively more complex than nonhuman animal culture (Horner et al., 2006; Marshall-Pescini and Whiten, 2008; Bentley and O'Brien, 2011; Kempe et al., 2014). Cultural transmission allows for cultural variants to be selected and adopted by individuals through a variety of social learning processes, such as those specific to copying action sequences that are associated with a specific end-state (imitation), as opposed to just learning about the end state (emulation) (Whiten et al., 2004, 2009b). Cumulative cultural evolution describes the process by which human culture tends to progress from simpler to more complex systems via cultural transmission. The iterated or incremental nature of accumulating adaptive modifications over time has been conceptualised as the *ratchet effect* (Tomasello, 1999; Tennie et al., 2009).

It has long been asserted that imitation is the dominant social learning mechanism that allows for the accumulation of beneficial knowledge, technologies and behaviours over time because of the capacity for high fidelity transmission (Boyd and Richerson, 1985; Tennie et al., 2009; Aunger, 2009; Mesoudi et al., 2013). However, individual social learning mechanisms, such as imitation and emulation, have not yet been well studied from an experimental viewpoint to help specifically explain patterns of change and variation in material culture (Mesoudi and O'Brien, 2009). For example, it is unknown which social learning mechanism, low copying fidelity mechanisms like emulation as opposed to high fidelity copying mechanisms might influence the establishment of long-term artefactual traditions. Also, the study how exactly different social learning mechanisms affect the continuous production of copying error in the manufacturing process has not been investigated within an explicitly empirical framework. Yet, such experimental endeavour would certainly illuminate the cultural transmission mechanisms necessary for the long-term perpetuation of the earliest of stable artefact lineages known to the archaeological record, such as the Acheulean (e.g., Mithen, 1999).

1.6 PhD project overview

Given the paucity of experimental investigation into the sources of variation and factors affecting such mutation rates, this PhD thesis was primarily based on experimental investigations targeted to further the understanding of isolated factors in the manual manufacturing process of artefacts that generate new variation (i.e., mutations) in material culture. Since few experimental investigations exist to date that generated specific answers as to the sources of variation in the archaeological record, the PhD project was focused on the empirical investigation of microevolutionary trends underlying change and variation in material culture in a controlled experimental setting. This will facilitate an enhanced and more detailed understanding of evolutionary processes in the actual artefactual record upon which selection biases (Bettinger and Eerkens, 1999; Mesoudi and O'Brien, 2008a) and drift act (Neiman, 1995; Shennan and Wilkinson, 2001). Additional investigation was also conducted to specifically answer the question exactly how specific social learning mechanisms (i.e., imitation and emulation) affect cultural variation and in material culture. The relationship between social learning and patterns of variation remains largely untested despite the predominant focus on social learning as one of the key mechanisms for the fidelity transmission of cultural variants over the long-term (Mesoudi and O'Brien, 2009; Shea, 2009).

1.6.1 Brief introduction to the experimental set-up of laboratory studies on variation

This PhD project was founded on experimental methods to enhance our understanding of trends and mechanisms specific to the study of material culture. In order to achieve this, the project employed experimental methods previously used predominantly in social and comparative psychology (Horner et al., 2006; Mesoudi and Whiten, 2008). The experimental set-up facilitated the examination of copying error in a controlled laboratory environment (where multiple environmental factors were held constant) which allowed the investigation and manipulation of specific factors regarding to the manual manufacturing process (e.g., differences in the learning context, tool and manufacturing traditions). The aim was to investigate cultural transmission in a context where all confounding variables were removed. The experimental context in that respect allowed the investigation of questions and hypotheses regarding the isolated influence of microevolutionary processes, for example, whether these were powerful enough to generate statistically significant patterns. Such empirical endeavour was achieved by generating directly observable cultural transmission processes in the laboratory context. The simulation experiments entailed the production of experimentally generated ‘artefacts’ that were produced by populations of study participants from daily materials and tools, like foam and plasticine and kitchen knives in a laboratory. These experimental simulations allowed for the detailed observation of the introduction of copying error when participants were asked to copy a specific ‘target form’ as accurately as possible. In addition, the project also benefitted from particular quantitative techniques used in archaeological studies termed *morphometric analysis* (Lycett et al., 2006; Buchanan and Collard, 2010b; Monnier and McNulty, 2010). Morphometric analysis is a statistical method adopted from the biological sciences and is designed for the study of shape variation. Specifically, it allows the capture of multivariate metric shape features of 3D cultural artefacts (Rohlf, 1990; Rohlf and Marcus, 1993; Adams et al., 2004; Slice, 2007). Since morphometric analyses are optimal to study shape differences between assemblages (Rohlf and Marcus, 1993; Lycett et al., 2006), this makes morphometrics an ideal tool to record and analyse shape mutations in the form of copying errors that are introduced in metric shape components. To emphasize, the experiments in this thesis were focused on the study of *shape* variation, as opposed to the study of merely *size* variation (Eerkens and Lipo, 2005; Kempe et al., 2012). Shape has long been utilised in biological sciences to understand variation, change and adaptations of biological organisms (Rohlf and Marcus, 1993; Slice, 2007) and recently gained utility in the study of evolutionary mechanisms in cultural artefacts (e.g., Lycett et al., 2006; Chitwood, 2014). Morphometrics are, therefore, optimal analytical methods designed to infer whether microevolutionary processes in shape features that are studied in isolation under the experimental paradigm can explain statistical patterns of variation in material culture.

1.6.2 Using Acheulean handaxe shape as a ‘model organism’

An additional factor that highlights the unique contribution of this PhD project to the study of evolutionary processes in archaeology was the utilisation of experimental methods commonly applied by biologists to study genetic mutations and phenotypic variation in the form of a ‘model-organism approach’. Model organisms, like the fruit fly *Drosophila melanogaster* or the bacterium *Escherichia coli* (Smith-Keary, 1988) utilised for genetic experiments have long been employed by evolutionary biologists because they facilitate the investigation of scientific interests into genetics on the basis of very simple and basic experimental designs which ultimately enhances the possibility to extrapolate accurate and robust results on evolutionary mechanisms underlying complex genetic events (Morgan, 1932; Dobzhansky, 1957; Ashburner and Novitski, 1976; Allen, 1978; Roberts, 1986; Greenspan, 2004; Ashburner et al., 2005).

The application of an analogous account of the model-organism approach in a cultural evolutionary context offers a variety of components that would be suitable for the study of the archaeological record, for example, higher controllability over factors of manipulation and also external factors (e.g., ecological) that may potentially affect the research data under investigation. Specifically, the experiments in this PhD thesis entailed the production of experimentally generated 3D replicas from everyday materials, such as foam and plasticine. These artefacts were based on the shape of the Acheulean handaxe (Chapter 2, Figure 2.1). Acheulean handaxes are archaeologically defined by a visual long axis which is shaped by invasive knapping to form a biface with a large cutting edge around the stone nodule of flake blank (Roe, 1976; Isaac, 1977; Schick and Toth, 1993; Gowlett, 2006). These stone tools are also characterised by a trend towards bilateral symmetry which, notably tends to vary considerably in temporal-spatial terms and even within individual collections (Clark, 1994; Lycett, 2008; Wynn, 2002). This Palaeolithic stone tool is one of the most prevalent culturally transmitted artefacts with findings stretching across western Europe and large parts of Asia since first appearing in Africa between 1.75 to 1.5 million years ago (Clark, 1994; Gowlett, 2011; Lepre, 2011; Beyene et al., 2013). Therefore, while the relatively simple ‘tear-drop’ outline does not require the most complex modification of shape structure, Acheulean biface morphology is also complex because it requires the manufacture of the entire three-dimensional core resource material while maintaining interrelated shape components. The challenge of modifying the entire core while having to consider a range of three-dimensional shape proportions allows for the generation of a large range of morphological variation and diversity in metric shape features (Gowlett, 1988). Gowlett (2006) mentioned that the manufacture of predetermined handaxe shape requires the careful modification of features such as length, breath and thickness components while keeping the multifactorial shape features in proportion. This was also the case in these experiments, since participants were faced with the challenge to copy multiple interrelated three-dimensional shape features of the target replica. For the various goals of the experiments, the Acheulean handaxe outline shape presented an optimal model for reasons similar to those selected as 'model organisms' in other scientific research.

There were several further specific reasons why reproducing a 'handaxe' form was chosen in the implementation of the 'model organism' approach adopted. First of all, the application of stone-tool knapping was not suitable within the frame of this experiment for reasons concerning safety and feasibility in a context that depended on recruiting large numbers of participants who were unfamiliar with stone tool manufacture. To accurately produce a handaxe form by stone requires skill, practice and experience that are built over months, even years, of intense practice (Edwards, 2001; Stout, 2002, 2005). Naturally, there were logistic issues recruiting populations of expert knappers within one experimental setting as knapping is not widely practiced exercise. In addition, it is possible to inflict severe injury during stone tool manufacture; therefore, safety was another concern (Whittaker, 1994). In these experiments these concerns were avoided by utilising simple every day materials like foam and plasticine because they contained specific advantages for the laboratory application such that standardised blocks of these materials were easily convertible into 'handaxe' shapes. This allowed the instantaneous recruitment of larger populations of participants who could successfully and feasibly master the physical manufacturing task even if they were not accustomed to stone-tool knapping or other craft-related tasks. In many ways, utilising Acheulean handaxes in the laboratory as a model organism carries specific advantages for experimental investigation analogous to the fruit fly *Drosophila melanogaster* in the biological sciences, such as quick generation turnover as well as cheap and rapid production. These characteristics carry the scientific advantage that large sample populations of artefacts could be produced in a relative short time frame. At the same time, Acheulean handaxes utilised as the cultural equivalent of 'model organism', still contain some of features of real world handaxes, such as shape and the 'reductive' manufacturing component. Hence, findings based on simulations utilising such model organism would still illustrate implications that are directly applicable to the archaeological record.

In addition, while feasibility is one reason why the Acheulean handaxe makes a particularly suitable ‘model organism’, the introduction of actual 3D material artefacts into the laboratory context appeals to the ‘external validity’ of this experimental research, at least compared to the ‘virtual laboratory’ (e.g., agent-based models such as the digital arrowheads utilised by Mesoudi and O’Brien (2008a) and 2D images of Acheulean handaxes used by Kempe et al. (2012)). Importantly, an experimental endeavour on the basis of physical 3D cultural artefacts allowed the simulation of some of the tactile, physical and procedural properties associated with the manufacture of real-world artefacts. The virtual laboratory is disadvantaged in that respect because it does not contain the ability to examine physical and tactile properties of the manufacturing process which is fundamentally relevant to all material artefact production.

1.6.3 Summary of study objectives and questions

Understanding the specific underlying processes that generate cultural variation and change on the microevolutionary level is essential to enhance a synthesised evolutionary theory specific to explaining processes of variation in material culture. With the exception of recent experimental approaches (e.g., Kempe et al., 2012; Gandon et al., 2013, 2014), studies to date have yet to address a number of key questions relating to how cultural artefact production manifests variation in the archaeological record.

The goal of this thesis was to deepen our theoretical and empirical understanding of the microevolutionary mechanisms that generate variation on the basis of copying errors in material cultural evolution that become introduced during the manufacturing process (McElreath et al., 2005; Shennan, 2008a; Mesoudi and O’Brien, 2009). The PhD project is targeted at providing robust answers to fundamental questions regarding whether microevolutionary processes of variation generation relating to the production of copying error, need to be more carefully and more fully considered during the analysis of statistical patterns of variation recorded in the archaeological record.

The project combines the utility of a model organism approach borrowed from the biological sciences, experimental models adopted from the psychology laboratory and analytical methods (i.e., morphometrics) specialised to identify metric shape variation in 3D cultural artefacts from the realm of archaeology. The contribution of this work is the novel combination of interdisciplinary models and methods that combine advantages in the study of evolutionary approaches to material culture.

Specifically, four distinct subsets of questions will be dealt with in turn in subsequent chapters:

1. What is the influence of contrasting artefact manufacturing procedures, such as irreversible (or 'reductive-only') processes as might be employed in stone knapping, compared with reversible manufacturing processes (or 'additive-reductive' processes), as might be employed in pottery manufacture?
2. What is the influence of varying time constraints during artefact production on copying error rates?
3. How do the contrasting social learning mechanisms of imitation versus emulation affect copying fidelity in material artefacts, and what are the potential implications of this for the observed perpetuation of artefact traditions?
4. Can simple differences of in manufacturing tools distinctively affect patterns of shape variation in artefactual traditions, even when other factors are common to situations?

Ultimately, the implications of the experimental results for issues pertaining to the examination of material culture variation in archaeological situations are discussed, both in individual chapters, and in the final discussion chapter.

Chapter 2 - Materials and methods

2.1 Choosing materials and tools for the research project

2.1.1 Choosing the tools and materials for experimental use

Since the ‘artefacts’ in the experimental investigations in this research were produced by populations of volunteer participants, the initial investigation of practical issues, such as the feasibility and safety of the tools and materials for the manufacturing process, was of primary concern. Before the research experiments were conducted, therefore, a variety of materials were investigated and evaluated against a set of criteria targeted to facilitate the selection of suitable raw materials. It was particularly important that materials were identified that facilitated the production of physical 3D shapes modelled after Acheulean handaxes, which are here also termed ‘replicas’. The initial tests of a variety of tools and materials were primarily done by the author in the autumn semester of 2010. Specific criteria were chosen (as summarised in Table 2.1) in an attempt to address questions regarding the feasibility of materials for manual manufacture. Most important were issues of cost, storage potential and utility (or ‘malleability’) during experimental procedures. At a later stage, combinations of selected tools and materials were tested in pilot experiments using small populations of voluntary participants.

The justification for running these initial tests was based on the knowledge that workability of materials and tools was particularly essential for successful experiments. There is little precedent science in the existing archaeological literature for experiments of this type. This is especially true for the production of physical 3D material cultural artefacts, which is largely absent in the experimental research directed specifically to evolutionary issues. Some exceptions may be mentioned, however, where simple material artefacts were applied within the context of ‘evolutionary’ experimental research. One of the only studies on copying error to date used the production of simple 2D shapes from paper and scissors (Eerkens, 2000). In a further example, Caldwell and Millen’s (2008) study on cumulative cultural evolution in the laboratory context was based on the production of 3D spaghetti and plasticine towers as well as paper aeroplanes. However, it should be noted that in this latter example, the object of the experiments was not expressly to study the *attributes* of the artefacts themselves. Given this lack of previous examples on which to draw, the study of suitable materials and tools for the experimental simulations merits particularly careful exploration. Here, the careful testing and consideration of a range of materials and tools was undertaken to assure the success of the experimental endeavour into the study of cultural evolutionary mechanisms in material culture.

2.1.2 Selection criteria for choosing suitable raw resource materials for the manual manufacture of 3D Acheulean handaxe replicas

The applicability of a range of materials was tested according to specific criteria (Table 2.1), which were specifically targeted to gain some insight into the performance of readily available materials for the specific nature of the experiments. For the sake of feasibility, one of the priorities was to choose materials that were easily workable and controllable (i.e., criteria of utility and successful completion in Table 2.1.). For example, manufacturing a block of raw material should not require excessive physical effort or strain. Also, only materials that facilitated the production of Acheulean handaxe replicas within the reasonable timeframe of around 30 minutes or less would be suitable. A further requirement was to select resource materials that were affordable in large quantities so it would be possible to run experiments relatively cheaply with populations of participants large enough to facilitate statistical testing. One criterion focused on the availability of the raw resource material in the format of standardised quantities in size dimensions, which would thus control for material starting conditions in each and every instance. The importance of utilizing standardised blocks of material was that any differences in the resulting shape variations in the experimental groups could be confidently attributed to the difference enforced by the experimental conditions, rather than to confounding effects due to heterogeneity in the starting conditions. In addition, materials were tested for appropriateness of post-experimental treatment and were generally discarded if not suitable for storage and post-experimental measurements; for example, in instances where shrinkage through drying would be a problem. Thus, in order to find suitable materials for the manufacture of replicas from every day materials, a variety of clays, waxes, soaps, sponge foam, plant foam and plasticine blocks were tested. Likewise, a range of every-day tools, such as different types of kitchen knives, scissors and vegetable peelers were also examined in the initial experimental trials in order to assess their feasibility and suitability for use in experiments of this type. The materials employed at this initial stage of testing were deemed safe for the utility of manual manufacture, since none of them contained toxic chemicals or physical hazards (e.g., sharp edges or splinters).

Table 2.1: Different types of raw resource materials chronologically ordered by suitability for the making of physical 3D Acheulean replica replicas.

Raw resource material	Type/ Brand	Successful completion	Cost	Storage	Utility	Availability of standardised blocks
Plant foam	Hard plant foam (Oasis Dry Sec)	Yes	Low	Yes	Solid yet malleable. Ideal for making 3D replicas	Optimally sized blocks available
Shower sponge	Soft sponge (IKEA)	Yes	Low	Yes	Soft but shape changes from handling which makes controllability challenging	Optimally sized blocks available
Plasticine	Newplast	Yes	Low	No	Optimal for 3D artefact production as not too soft	Standardised blocks to desired measures
Soap	Cussons Imperial Leather	Yes	Low	Yes	Fairly soft, optimal	Too small
	Sainsbury	Yes	Low	Yes	Too hard, not optimal	Too small
Candle wax	Cylinder formed (Wilkinson)	Yes	Medium	Yes	Too hard, not optimal	Standardised blocks to desired measures
	melted from flakes (Canterbury Wax Shop)	No	High	Yes	Too hard, not optimal	Standardised blocks to desired measures
	melted from flakes (IKEA)	No	Medium	Yes	Too hard, not optimal	Standardised blocks to desired measures
Clay	Keraplast	No	Medium	Yes	Shrinkage effects	Standardised blocks to desired measures
	GEDEO	No	Medium	Yes	Shrinkage effects	Standardised blocks to desired measures

Initial testing was done by the author, purely to determine if any of these materials might provide suitable candidates for more formal feasibility trials with volunteer participants. On the basis of these initial, informal trials, a number of issues were identified (Table 2.1). In terms of controllability and workability, the plant foam was most suitable because the hard foam was resilient against involuntary modification from simply handling the foam, yet it was sufficiently malleable to cut the foam into desired shapes. The soft sponge was also suitable, but lacked controllability because during manufacture the shape was temporarily altered, adding a non-desired physical aspect into the overall experimental condition. The *Newplast* plasticine was also suitable for the production of 3D replicas. The only disadvantage concerned the storage of plasticine replicas, since storage could lead to involuntary modification of shape properties. Since plasticine was otherwise optimal in terms of safety, utility, cost and availability of suitable standardised blocks and because it was the only material optimal for the scientific investigation of the effects of both reversible and irreversible manufacturing processes on rates of copying error within one experimental context, it was chosen for one of the main experiments of the research project. For the single experiment that utilised *Newplast* plasticine, which is described in Chapter 3, this storage issue could be successfully countered by recording shape properties of plasticine replicas immediately after production via standardised photographic images. Further details regarding the selected tool and the description of the standardised plasticine blocks can be found in Chapter 3, and will not be discussed here further.

Thus, since the foam, sponge and plasticine far excelled compared to the wax, soap and clay materials, these less suitable materials were discarded from further implementation in the pilot studies. The reason for discarding soap as a suitable material was mainly because the soap was only available in relatively small sizes. The waxes tested were generally too hard for effective handling and therefore required a level of physical effort that prohibited the successful completion of any replicas on the basis of applying simple every-day cutting tools. The clays suffered from shrinkage effects during the drying process, which inevitably introduced confounding shape variation and was therefore also rejected.

The different types of scissors, peelers and kitchen knives used for the initial testing proved to be both safe and successful for the manufacture of 3D cultural artefacts, although the peelers and kitchen knives worked most suitably with the foam blocks.

2.1.3 Pilot studies to test further combinations of selected materials and manufacturing tools

The knowledge gained from these initial material and tool trials was used to conduct a range of pilot experiments in the second semester of the first year (spring semester 2011). This time, the selected raw materials from the initial testing phase were trialled in combination with a set of manufacturing tools in a small population of voluntary participants. At least 15 volunteers were recruited for each material and tool combination, and there were 100 volunteers in total who participated in these pilot experiments. The floral foam was trialled in combination with three tools, a simple plastic knife and two different vegetable peelers (left section of Table 2.2). One of the vegetable peelers (the plastic-handled peeler) had the blade placed as a direct extension of the handle. By contrast, the metallic peeler had the blade placed perpendicular to the handle. As opposed to the plastic-handled peeler, which had an immobile blade, the metallic peeler's blade had a motion flexibility of about 90°. The sponge was combined with two types of scissors of contrasting sizes, small (13.78cm in length) and large (22.26cm in length). Thus, the floral foam was tested in combination with three manufacturing tools and the sponge was combined with two tools (Table 2.2).

The aim of these pilot experiments was to ensure that participants with little to no experience in manual manufacturing and crafting tasks could successfully operate a combination of daily materials and tools within a manageable time and safe context. A primary goal was therefore to observe whether naïve participants could successfully employ a combination of these materials and tools to produce 3D replicas (each participant produced one replica). In other words, it was investigated whether the participants managed to complete artefact products without facing major physical challenges in working with the tools and materials. The knowledge and results gained from running these pilot experiments was essential to improving the success and achievability of the experimental research studies. It might be emphasized that for this stage, the main priority of this investigation was placed on testing practical aspects only as opposed to focusing on generating meaningful results. All volunteers were recruited by word of mouth from the School of Anthropology and Conservation at the University of Kent. The general procedure for these experiments reflected, in general terms, the experimental procedure implemented at later phases of the project; that is, all volunteers were asked to faithfully copy the shape of a target form within a set timeframe of 30 minutes. The target form provided to the participants was manufactured from the same material as the material given to the volunteers for the manufacture of their own replica. Thus, there was one target form produced from floral foam for the foam group and there was one sponge target form for the sponge group. All participants began the manufacturing process in a uniform fashion from standardised blocks of material to control for confounding effects resulting from heterogeneous starting conditions.

Table 2.2: Overview of initial material and tool combinations. The plastic-handled peeler, metallic peeler and plastic knife were applied to the plant foam (left section of the table). Two differently sized scissors were applied to shower sponge (right side of the table). In each of the material groups, participants were asked to faithfully copy shape and form of a target form made from the same material. There were roughly 15 voluntary participants for each material and tool combination.

Plant foam group	**Material**	**Sponge foam group**	**Material**
Plant foam (sample)		Shower sponge (sample)	
	Tools		**Tools**
Plastic-handled peeler		Small scissors	
Metallic peeler		Large scissors	
Plastic knife			

2.1.4 Materials chosen for the study of the impact of evolutionary mechanisms on artefactual attributes

Overall, all tools and material combinations chosen for the pilot experiments were met with success by the participants. Participants succeeded in all tool conditions without complications, all tools and materials proved suitable for physical replication tasks. In addition, the materials and tools were all fairly cheap (less than £1 per material block), which allowed for the affordable supply of tools and materials for large sample groups of participants.

When drawing more specific comparisons, however, the floral plant foam was the preferred material over the sponge. As opposed to the hard dry floral foam the sponge's soft material constantly changed form and shape during the manufacturing process which impaired the control over the copying process and increased the risk of introducing a considerable amount of undesired variation in the form of 'noise' during the copying process. The floral foam on the other hand was particularly promising for the further study of evolutionary mechanisms using 3D physical replicas. The floral foam consists of stiff material, which enhances the control over the manufacture. It also provided ideal conditions of workability since it was easily modifiable such that even small shape changes could be copied during cultural transmission. Yet, thanks to its general robusticity, the handling of the foam during manufacture did not introduce unwanted shape modifications.

As can be viewed in Figure 2.1, participants in the floral foam and tool combinations required less than 20 minutes to complete the manufacture of their replica. This was a relevant finding because it meant the time frame provided for task completion of the experiments in the research project was feasible in practical terms.

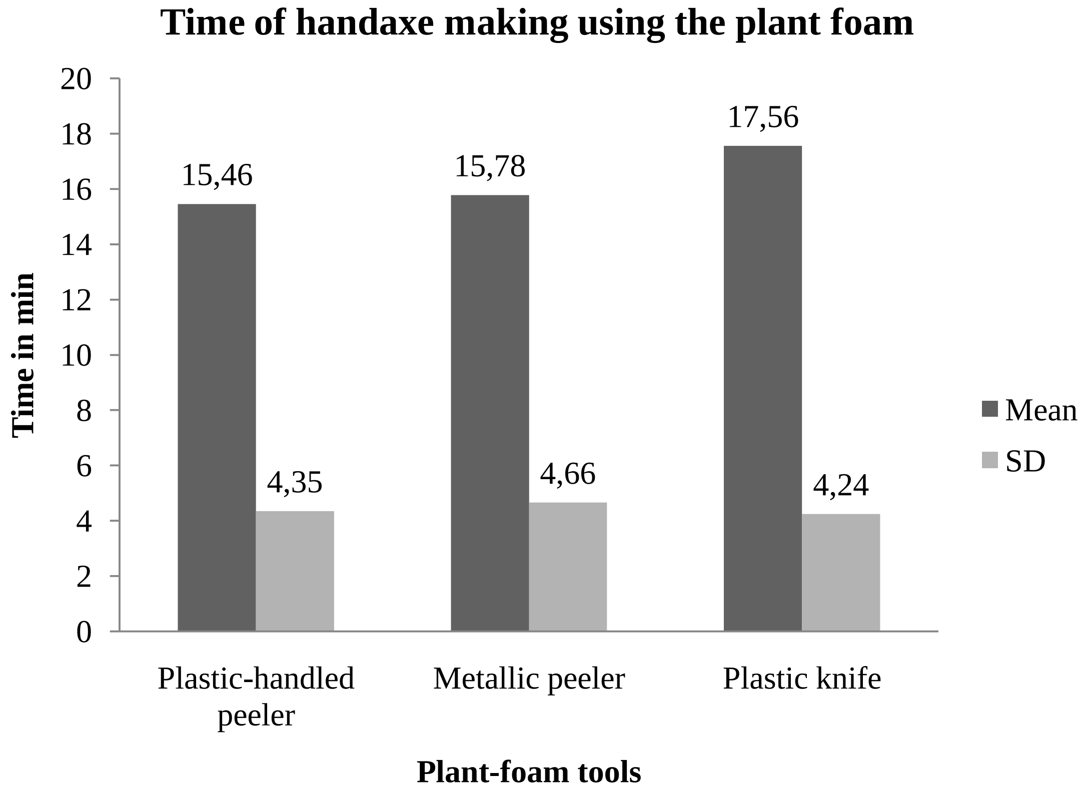

Figure 2.1: Mean time and standard deviation for the manual manufacture of replicas produced from the floral foam and the different tools.

2.1.5 The utility of the floral foam as the predominant raw resource material used in the research project

Since the floral foam constituted the most suitable material for experimental use, a more detailed description shall be provided because it was utilised for the majority of experiments in this research project. The floral dry foam of the type ‘Oasis Dry Sec’ is supplied in machine-cut standardised blocks and consists of a type of dense, porous and hard floral foam (Figure 2.2). A standardised block of floral foam measures 22.3cm in length, 11cm width and 7.8cm in thickness. This type of hard foam is reminiscent of materials such as polystyrene and is typically intended to create a bed for artificial plants and to hold the plant stem firmly. At the same time, the foam is specifically designed to be malleable so that it can be easily cut into desired shapes using every day household tools such as scissors or knifes for ease of placing and positioning within a variety of receptacles. In many respects, the material was ideally suited for the research experiments as it is a relatively stiff, resilient material, where the simple handling of the foam was not enough to introduce any undesired shape modifications. Yet, it could be easily shaped by participants using every day cutting tools, thus exerting high control over the shaping process. During these trials, it was observed that the plastic knife and metallic peeler could be readily used by the participants to manipulate and shape the blocks (Figures 2.3 and 2.4).

Figure 2.2: Example of machine-cut foam blocks provided to participants during experiment. Each block measured 22.3×11×7.8cm.

In sum, based on these systematic investigations of a variety of materials and tools and the recruitment of 100 voluntary participants, the predominant material chosen for experimental application was the Oasis Dry Sec plant foam. This was used in combination with two selected tools: the metallic peeler and the plastic knife. In addition, the utility of the *Newplast* plasticine was also reserved for one particular experimental context on the study and simulation of reversible and irreversible manufacturing traditions, as described in Chapter 3.

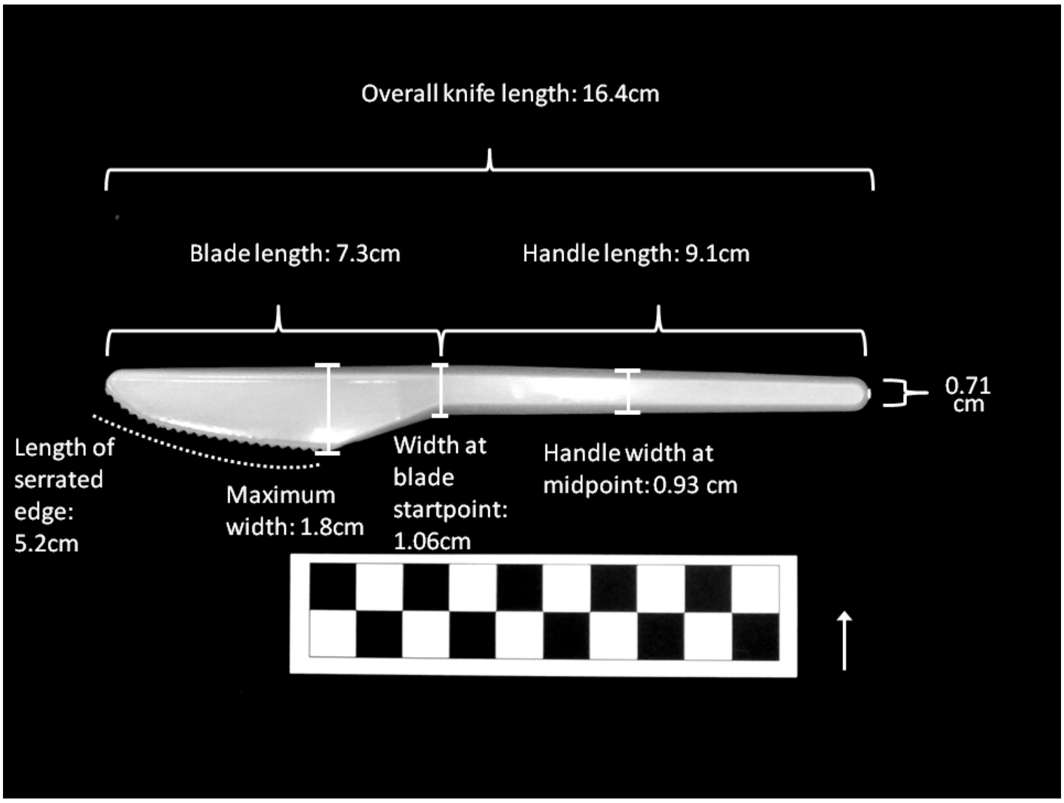

Figure 2.3: Dimensions of the plastic knife used by participants to generate replicas from floral foam.

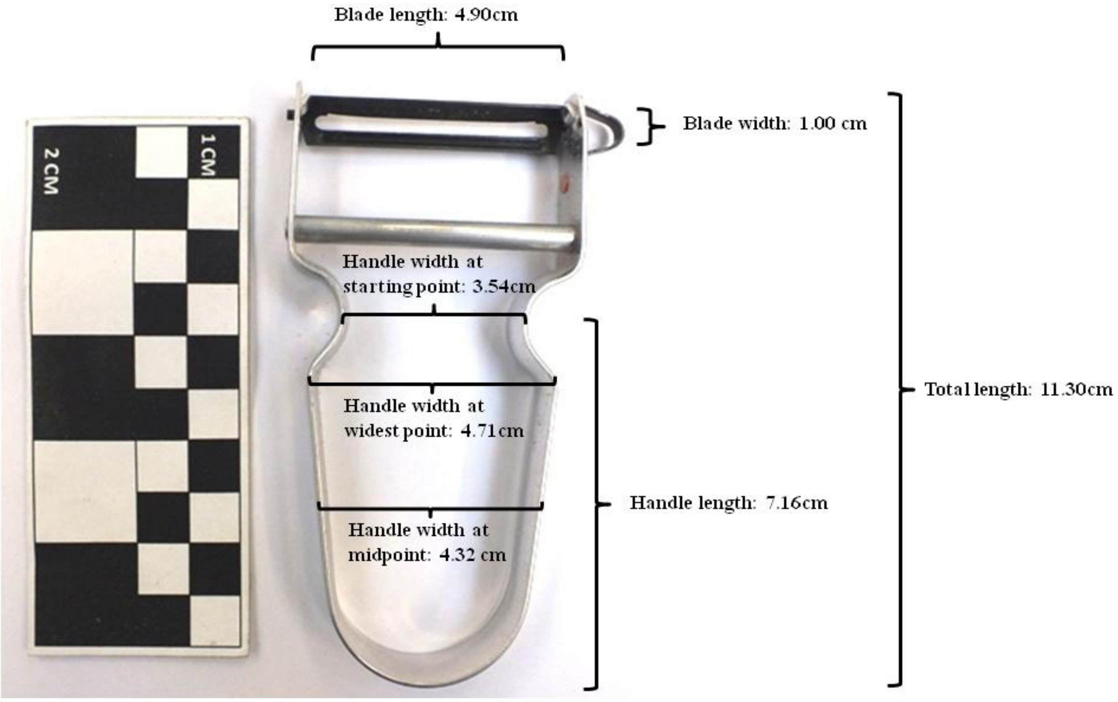

Figure 2.4: The metallic peeler with flexible blade (motion flexibility of 90°).

2.2. Introducing morphometric analysis for the study of shape variation

The remainder of this chapter is dedicated to describing in detail the procedure for how shape data from a variety of morphometric variables were obtained from the replicas that were manufactured during the experiments. The procedure for the standardised orientation of the replicas, and the steps undertaken to obtain metric shape data via morphometric analysis, was uniform across all experiments presented in this thesis.

Before providing the detailed description of the procedural steps undertaken to obtain the metric shape data, it may be necessary to provide an explanation why morphometric shape analysis was chosen as part of the research project. Morphometric analysis is an analytical framework based on conducting multiple measurements that allows the quantification of form, which includes both shape and size aspects. Traditionally, morphometrics has been used to study phenotypic similarity between morphological structures, such as skeletal remains, in the study of heredity for example (e.g., Hallgrímsson et al., 2008) amongst other aspects in the sciences of palaeoanthropology surrounding shape variation (Slice, 2007). Morphometric analysis has also been successfully applied to study and quantify shape variation in cultural artefacts, such as stone tools, because morphometric analysis facilitates the precise and scientific investigation of metric shape variation (e.g., Lycett, 2007b; Costa, 2010; Chauhan, 2010). Morphometric analyses also facilitate the advantage of separating shape from size effects (e.g., Rohlf, 1990; Jungers et al., 1995; Buchanan and Collard, 2010b; Costa, 2010). Here, the utility of morphometric analysis was employed to investigate shape variation in the experimentally produced replicas.

An orientation protocol was developed to quantify the shape data of the replicas in a standardised and replicable manner. This orientation protocol ensured that the measurements taken at specific points of a replica outline were directly corresponding to those measurements taken at equivalent points of another replica. High precision in the correspondence between measurements taken was crucial to accurately capture shape inconsistencies as a result of shape error between replica specimens that were introduced during manufacture.

2.2.1 The terminology used to describe experimental 3D replicas

The terminology used to physically describe the experimental replicas is shown in (Figure 2.5). The orientation protocol was designed specifically to retrieve measurements from two different image (photographic) perspectives of each replica. One image perspective was termed ‘plan-view’, which captured the 2D perspective of the front of the replica. The plan-view perspective is visualized on the left image in Figure 2.5. The term ‘profile-view’ referred to the side view of the replica, or lateral perspective, and is depicted on the right in Figure 2.5. Recording measurements from the plan- and profile-view of the replica allowed for morphological shape components to be systematically captured for the entire three dimensional form.

The upper boundary of an experimental replica was termed the ‘distal end’, whereas the lower end of a replica was described as the ‘proximal end’. The sides of the replica face were referred to as right lateral or left lateral margins.

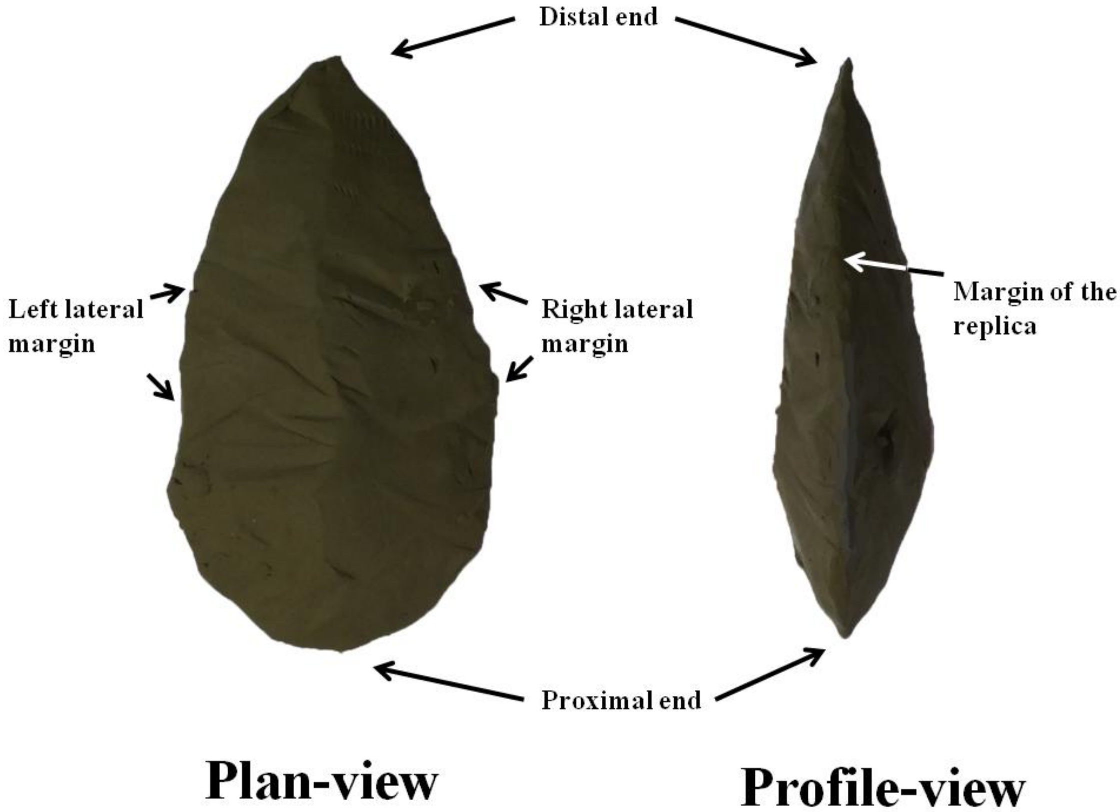

Figure 2.5: Illustration of the morphological terminology commonly used on the example of an experimentally produced plasticine replica.

2.2.2 Obtaining standardised photographs: introducing the camera set-up

Since the morphometric shape analysis was undertaken on digital photographic images from the plan- and profile-views of the replicas, a standardised camera set-up was employed. The camera set-up contained a copy stand (Kaiser copystand 'Reprokid') attached with a Fujifilm DSLR camera (Finepix HS 20 EXR), lens (30x zoom lens: 24-720mm), and a light box (Jessops, 20.3cm x 25.4cm).

Standardised high quality photographs of the replicas were captured with a DSLR camera that was securely held on the copy stand with the camera at a focus directly parallel to the baseboard. The camera was consistently secured to the support column at 60cm as defined by the column's scale bar. On the baseboard a portable lightbox was placed. The lightbox ensured accurate discrimination of the replicas' outlines from the background (Figure 2.6).

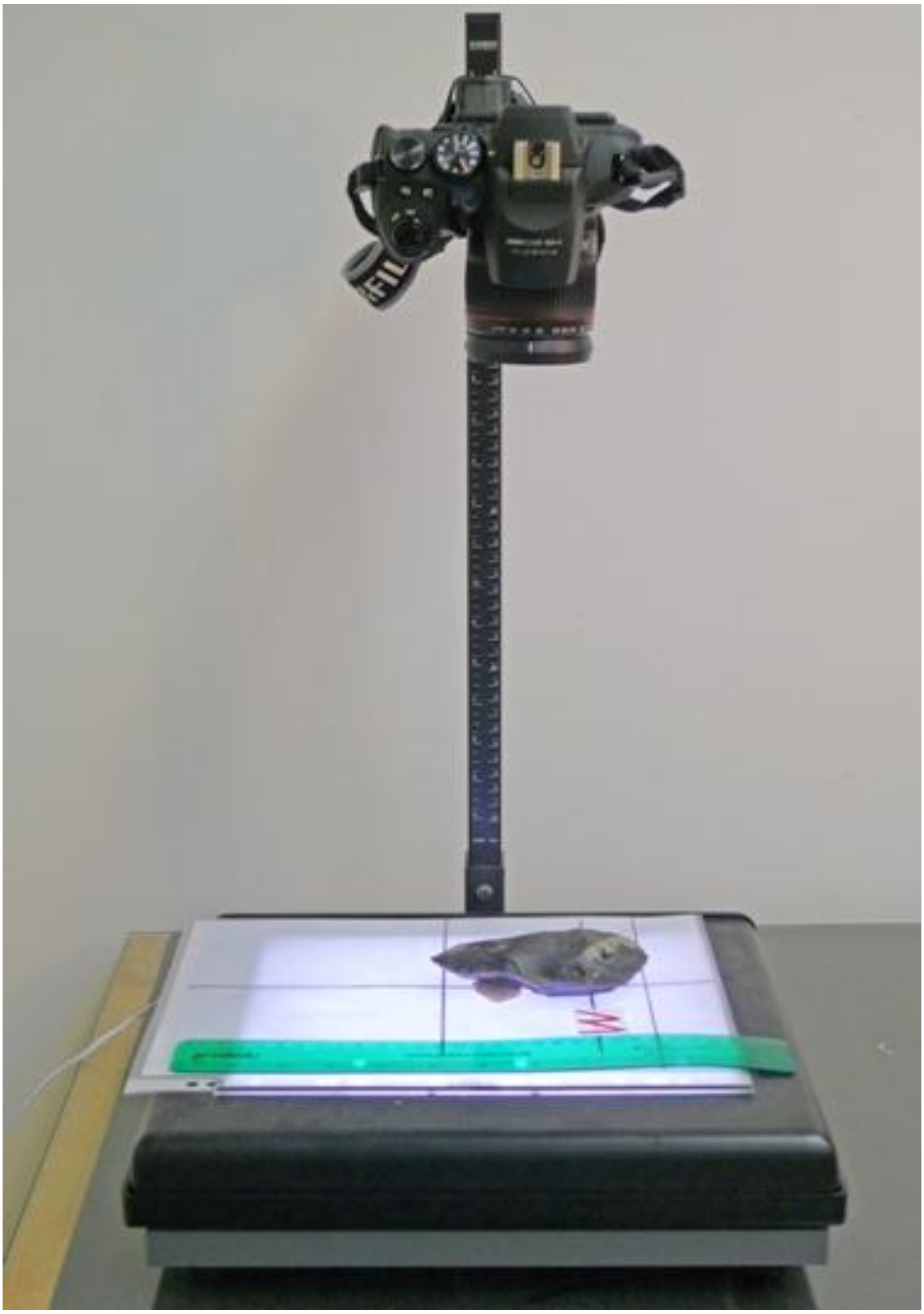

Figure 2.6: Camera set-up to produce standardised 2D images.

2.2.2.1 Photograph: the plan-view

One photograph per replica was obtained from the plan-view perspective for further analysis (Figure 2.7). Every replica was placed so that the ‘poles’ of the width and length axes were positioned at the same distance to the baseboard in order to hold the central plane of the replica at a level parallel to the baseboard. The replica was secured with plasticine to support its position and was placed centrally underneath the camera focus. A photographic scale bar (10 cm) was position alongside the height of the width and length poles. In order to accurately establish the equivalence between the participant's own manufactured replica and the copied target form during this photographic procedure, each participant was asked to point out the corresponding faces between the two replicas (referred to as 'front' and 'back').

2.2.2.2 Photograph: the profile-view

To obtain the photograph for the profile-view perspective, the replica was rotated orthogonally from the plan-view so that the right lateral margin was turned upward and the central plane of the replica was aligned vertically to the baseboard (Figure 2.8). The scale bar was height-adjusted to the thickest point of the replica.

2.2.3 Orientation protocol for the plan- and profile-view

The orientation protocol for the plan and profile-view of the replicas was composed of two major procedural steps. To begin the orientation protocol, the tip as the point of orientation was located. The tip was identified by determining the maximum length line of the area of the replica and defined as the point where the maximum length line intersected the boundary of the distal end. The maximum length was determined digitally on the photographic representation of the replica by utilising software tpsDig (version 2.16; Rohlf, 2010), which is expressly designed for obtaining electronic measurements.

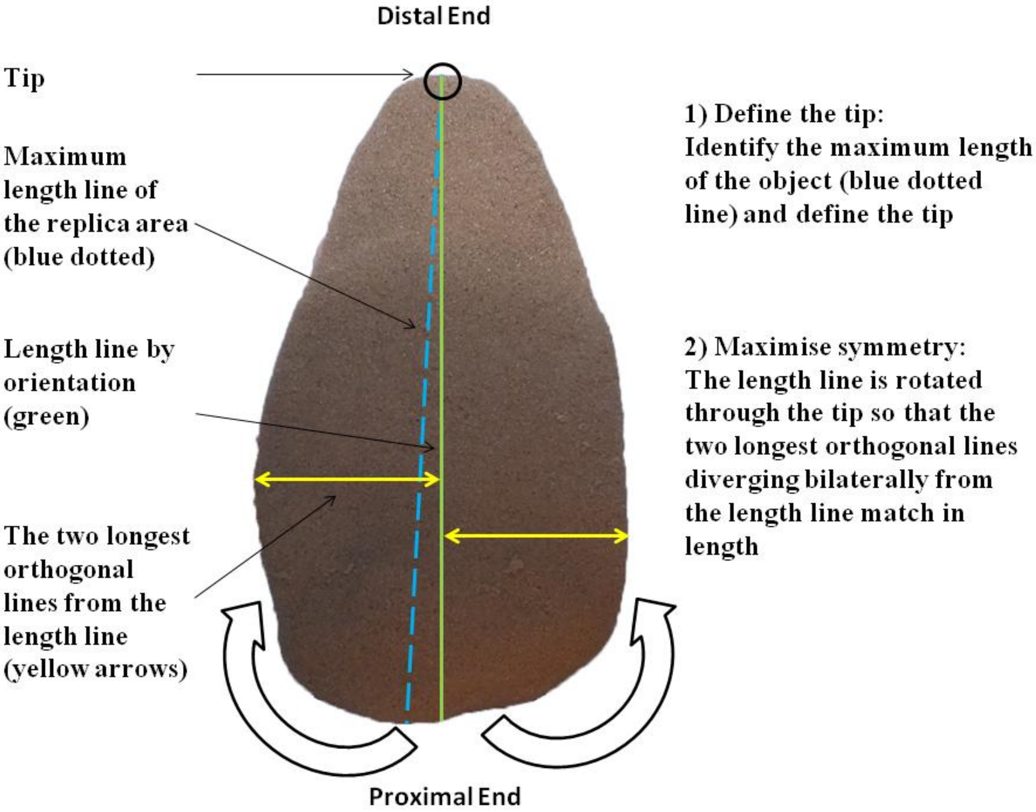

Figure 2.7: Orientation protocol illustrated on the plan-view of a foam replica.

In the following step, the replica was rotated through the tip so that the length line was positioned such that the two longest orthogonal lines diverging bilaterally from this length line were equal in length (Figure 2.7). The orientation protocol utilised here was an alternative version of that originally developed by Callow (1976), which was also later implemented by Costa (2010). The major difference between the orientation protocol employed here and that by Costa (2010) was that a point of orientation was not defined in Costa’s work. However, since the experiments in this research project comprised the generation of replicas that potentially assumed extreme shape deviations, the identification of a point of orientation *by definition* was crucial to be able to maximise equivalence between the measurements of all replicas, even in extreme cases of shape divergences. A visualisation of the orientation procedure for the profile-view can be found in Figure 2.8.

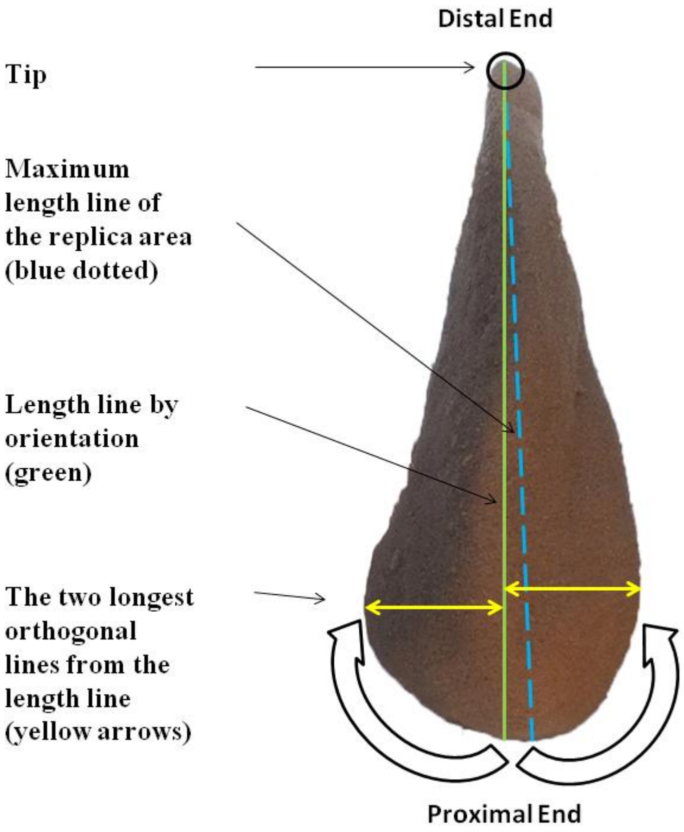

Figure 2.8: Standardised orientation of the profile-view.

2.3 Measurement scheme for morphometric variables

2.3.1 Description of the measurement scheme

A digital measurement grid was placed onto the photographic representations of each replica to obtain a series of lateral and bilateral measurements from the plan-view and profile-view perspectives. Similar measurement frameworks referred to as 'comb' configurations have previously been employed by Buchanan and Collard (2010a) and Monnier and McNulty (2010). The comb figuration is a straight-forward and effective method to obtain the shape outline of experimental replicas in a reliable fashion. The measurement grid was digitally generated in *Microsoft PowerPoint* and was composed of a series of horizontal lines that diverged bilaterally from the grid's central line at predefined distances (Figure 2.9). The grid was generated to capture the shape 'outline' of each replica's area. The 'outline' can be defined as the "line following the maximum extremity of a nucleus that can be drawn around its mass" (Lycett, 2007b, p.1437). The grid's horizontal lines were systematically positioned at distances of ten percent. Additional gridlines were placed at interval of five percent, fifteen percent, eighty-five percent and ninety-five percent of length. These supplementary measurements at the distal and proximal regions of each replica served to capture additional shape information at the ‘tip’ and ‘base’ ends of each specimen. All measurements captured from the plan and profile-views were recorded following orientation of the replicas. Measurements that were not predefined by the measurement grid, such as maximum width and thickness were also recorded at a line perpendicular to the maximum length line by orientation.

2.3.2 Placing the measurement grid

For both the plan- and profile-view, the measurement grid was superimposed onto the digital image of the replica so that the grid’s central line was placed above the maximum ‘length line by orientation’. The upper and lower boundaries of the grid were adjusted to the maximum length margins of the replica’s area (Figure 2.9). The grid was digitally manipulated so that the multiple horizontal lines connected to the lateral boundaries of the replica area. Since the grid boundaries were equivalently placed onto the maximum length margins of the replica in both the profile- and plan-view, the measurements of the profile-view were directly orthogonal to the measurements at the corresponding percentage points of the plan-view.

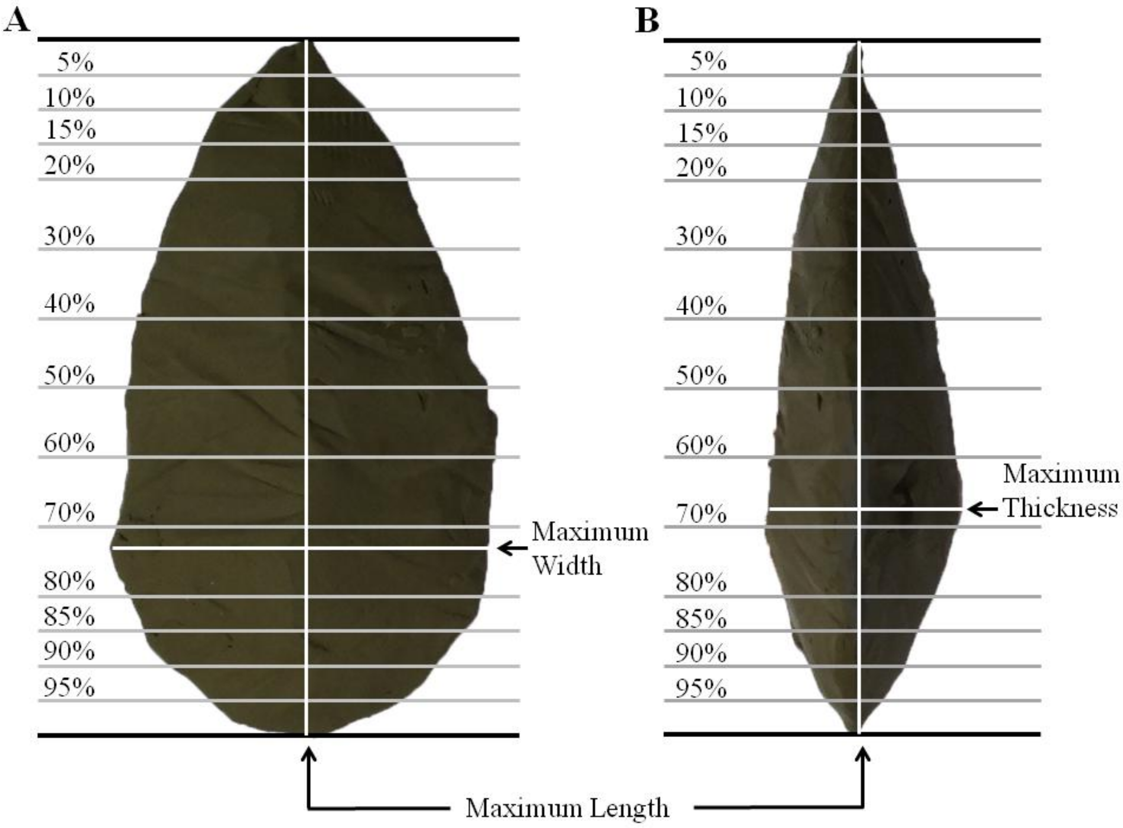

Figure 2.9: The measurement grid placed on a plasticine replica bisects the replica at the maximum length line by orientation. (A) Plan-view with grid. (B) Profile-view with grid.

2.3.2.1 Defining the measurements for the plan-view

Bilateral measurements were taken from the maximum length line to either side of the lateral boundary at the according percentage points of the measurement grid in a systematic fashion. Therefore, measurements oriented to the left of the maximum length line were referred to as the ‘left lateral’ segment (Figure 2.10 A) and measurements positioned to the right from the maximum length axis were described as the ‘right lateral’ segment (Figure 2.10 B).

The measurements taken from the plan-view contained 13 left-lateral and 13 right-lateral width measurements together with an additional two lateral measurements for maximum length and maximum width. Altogether, a sum of 28 measurements was captured for the plan-view, as visualized in Figure 2.10.

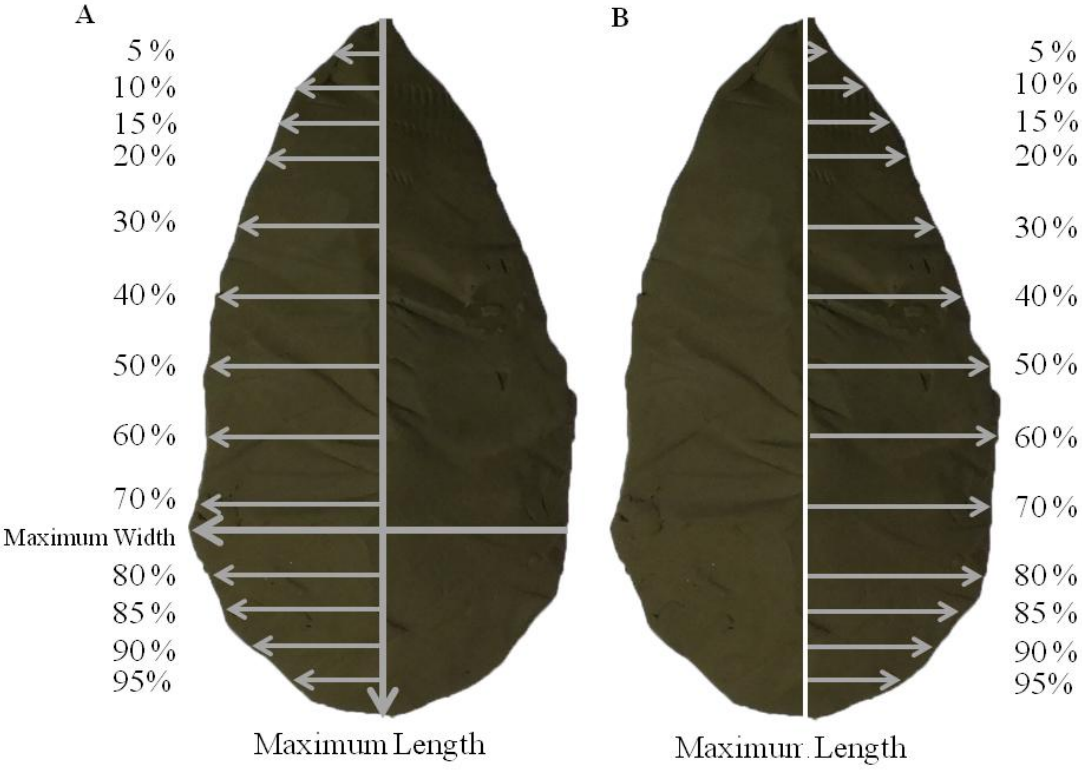

Figure 2.10: These pictures illustrate the measurements taken from the plan-view. A) Display of the measurements taken from the left lateral segment together with maximum width and length. B) Display of the measurements obtained from the right lateral segment.

2.3.2.2 Defining the measurements for the profile-view

For the profile-view, 14 lateral measurements were recorded between the distances of the lateral boundaries at the defined percentage points plus one additional lateral measurement for maximum thickness (Figure 2.11). Altogether, the plan- and profile-view contained measurements for a total of 42 morphometric variables; a list of the morphometric variables can be viewed in Table 2.3.

Figure 2.11: Lateral measurements taken from the maximum length line of the profile-view of a plasticine replica.

2.3.3 Obtaining measurements from digitized images

Utilising digital methods for morphometric analysis is a time-saving alternative to more traditional methods to obtain high-quality morphometric data, and has been shown to lead to greater replicability (e.g., McPherron and Dibble, 1999). To electronically record measurements from the photographic representations of the replica, a digital (jpg) image of each replica with the superimposed measurement grid was imported into the freely available software tpsDig2 (version 2.16; Rohlf, 2010). For each photograph, the scale factor was determined from the 10cm scale bar depicted on the photograph. Each measurement was drawn at a desired distance X-X’ utilising the cursor; for each distance drawn, the software automatically calculated the distance in centimetres. The measurements were rounded to the nearest millimetre. For every photographic image measured, the entire set of measurements was automatically added to a downloadable text file. A screenshot visualising the digital measurement procedure can be viewed in Figure 2.12.

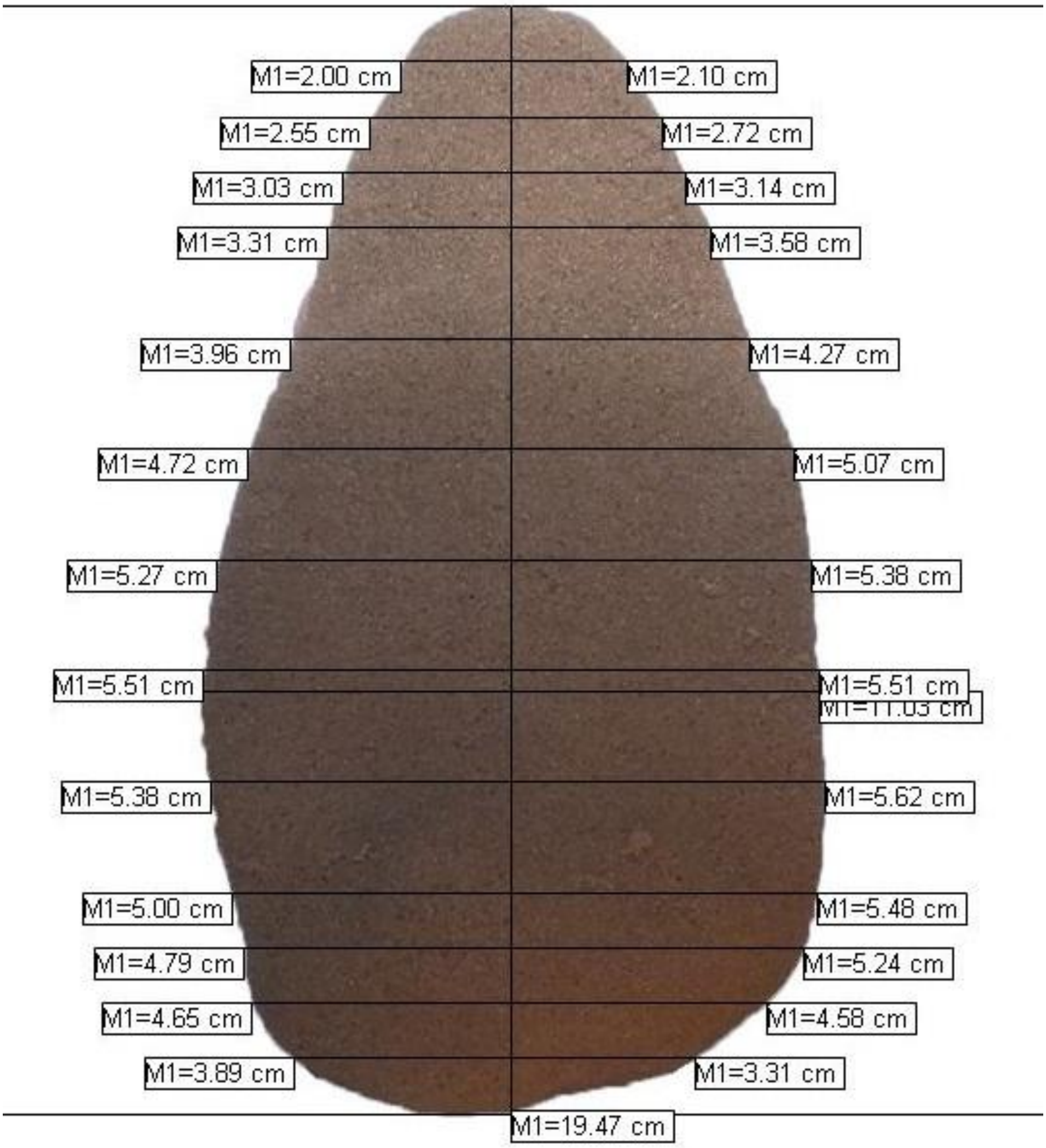

Figure 2.12: Sample of the set of digital measurements obtained from the electronic image of a replica's plan-view.

Table 2.3: List of morphometric variables

	1.	Maximum length
	2.	Maximum width
	3.	Maximum thickness
Plan-view	4.	Left lateral width at 5 % maximum length
Left-lateral variables	5.	Left lateral width at 10 % maximum length
	6.	Left lateral width at 15 % maximum length
	7.	Left lateral width at 20 % maximum length
	8.	Left lateral width at 30 % maximum length
	9.	Left lateral width at 40 % maximum length
	10.	Left lateral width at 50 % maximum length
	11.	Left lateral width at 60 % maximum length
	12.	Left lateral width at 70 % maximum length
	13.	Left lateral width at 80 % maximum length
	14.	Left lateral width at 85 % maximum length
	15.	Left lateral width at 90 % maximum length
	16.	Left lateral width at 95 % maximum length
Plan-view	17.	Right lateral width at 5 % maximum length
Right-lateral variables	18.	Right lateral width at 10 % maximum length
	19.	Right lateral width at 15 % maximum length
	20.	Right lateral width at 20 % maximum length
	21.	Right lateral width at 30 % maximum length
	22.	Right lateral width at 40 % maximum length
	23.	Right lateral width at 50 % maximum length
	24.	Right lateral width at 60 % maximum length
	25.	Right lateral width at 70 % maximum length
	26.	Right lateral width at 80 % maximum length
	27.	Right lateral width at 85 % maximum length
	28.	Right lateral width at 90 % maximum length
	29.	Right lateral width at 95 % maximum length
Lateral variables	30.	Lateral width at 5 % maximum length
	31.	Lateral width at 10 % maximum length
	32.	Lateral width at 15 % maximum length
	33.	Lateral width at 20 % maximum length
	34.	Lateral width at 30 % maximum length
	35.	Lateral width at 40 % maximum length
	36.	Lateral width at 50 % maximum length
	37.	Lateral width at 60 % maximum length
	38.	Lateral width at 70 % maximum length
	39.	Lateral width at 80 % maximum length
	40.	Lateral width at 85 % maximum length
	41.	Lateral width at 90 % maximum length
	42.	Lateral width at 95 % maximum length

2.4 Procedure for estimating intra-observer reliability

An intra-observer reliability test was conducted to test the reliability of the raw measurement data sets that were obtained following the procedural steps of the orientation protocol. Ideally, the procedure of standardised orientation ought to minimize measurement errors; however, an intra-observer reliability test specialised for multivariate morphometrics (White, 2000, p. 307) was used here to test whether the procedure for obtaining multivariate measurements in these research experiments was robust and reliable.

To begin with, three sets of measurements for the 42 morphometric variables derived from three experimental replicas were completed for the test. The three replicas were randomly chosen from the foam group in the pilot experiments. The measurement sets were conducted for each of the replicas on three consecutive days so that a measurement data set was recorded only once per day for each of the three replicas. According to White (2000), spacing the recording of the measurement data sets of the same replica at a minimum of 24 hour intervals allows for large enough time gaps so that the previous knowledge regarding the details of the previous measurement does not interfere with consecutive measurements. This means that every 24 hours for three days, each of the three foam replicas underwent the complete measurement procedure from standardised orientation, the taking of the photographs from the plan- and profile-views and the recording of the complete set of digital measurements via placement of the measurement grid.

The measurement error for the intra-observer test was calculated as follows. To begin with, a mean was calculated from the three measurements of each morphometric variable (see an example on the maximum thickness variable of one of the three replicas in Table 2.4).

Table 2.4: Generating a mean from repeated measurements for the intra-observer reliability test.

Sample replica 2

Variable	**Day 1**	**Day 2**	**Day 3**	**Mean**
Maximum Thickness	7.55cm	7.57cm	7.68cm	7.60cm

In the next step, each of the three measurements was subtracted from the mean. This difference gave an indication of the deviation of each measurement from the average measurement. Table 2.5 lists the deviation from the mean for each of the three measurements for the maximum thickness variable. Then, the mean is also calculated from these three deviations.

Table 2.5: Generating an average measurement error for the intra-observer reliability test.

Sample replica 2 **Deviation from the mean**

Variable	**Measurement 1**	**Measurement 2**	**Measurement 3**	**Average measurements error**
Maximum Thickness	0.05cm	0.03cm	0.08cm	0.053cm

Finally, the mean of the measurement error was divided by the mean of the measurements and displayed as a percentage measure. For the example of the maximum thickness variable in Table 2.4 and Table 2.5 the calculation looked as follows: 0.053cm /7.60cm = 0.00697368 = 0.7%. Therefore, for the maximum thickness variable, an error score of 0.7% was calculated. Naturally, the procedure was repeated for each of the 42 morphometric variables for each sample replica separately. The calculated score for measurement error informs about repeatability and reliability of the measurement, however, measurements above a score of 5% measurement error were regarded as failing the reliability test.

To give an indication, the average error calculation across 42 variables for the first replica was 2.03%, for the second replica the average error was 1.25% is and for the third replica the average error score was 0.93%. Given that the procedure for obtaining measurements generated measurement deviations of less than 5% error, it was therefore concluded that the standardised orientation protocol and the multivariate morphometric analysis conducted in the research experiments was accurate and reliable.

2.5 The calculation of shape data: size adjustment procedure

Since this PhD project was focused on monitoring shape-related changes in the designs of experimentally generated replicas, controlling for size effects while retaining shape data was an essential part of the analysis. The process of removing size effects from data in favour of investigating shape variables is referred to as *size adjustment*. The elimination of size effects was done via the process of calculating the geometric mean for morphometric measurements, because the geometric mean is an overall proxy of size (Jungers et al., 1995). The method of calculating the geometric mean was originally developed by Darroch and Mosiman (1985). As described by Jungers et al. (1995, p.144), the geometric mean can be computed as the "*n*th root of the product of all *n* variables". In more specific mathematical terms, the geometric mean derived from a series of *n* variables ($a1$, $a2$, $a3$ ... a_n) is correspondent to $\sqrt[n]{a_1 \times a_2 \times a_3 \times \ldots \times a_n}$. Size-adjustment via the geometric mean method has been demonstrated to efficiently control for scale between objects by creating a 'dimensionless scale-free variable' whereby the original shape data are preserved (Falsetti et al., 1993; Jungers et al., 1995). The geometric mean was calculated for each replica separately and size-adjustment was completed when each measurement belonging to the corresponding morphometric variable was divided by the geometric mean.

Further steps taken to obtain data used in particular analyses (e.g., participant copying error) are described in individual chapters.

Chapter 3 - Copying error and the cultural evolution of ‘additive’ versus ‘reductive’ material traditions: an experimental assessment

3.1 Introduction

The key element of Darwin’s descent with modification that is of main focus in this chapter is the generation of variation. As Eerkens and Lipo (2005, p. 317) put it, “[v]ariation is the raw material upon which selection operates to cause changes in the frequency of cultural traits through time”. To date, little is known about how microscale changes that get introduced during manual manufacture as a result of human copying error affect evolutionary trends and how these can lead to long-term design modifications (Eerkens, 2000). Importantly, Palaeolithic stone tools, which are the result of complex reductive knapping techniques, express a vast array of morphological design manifestations, which vary perceptibly between individual assemblages and have been illustrated to create significant statistical trends in shape and form on the population-level (Gowlett, 2006; Lycett and Gowlett, 2008). As Gowlett has stated: “in any set of Acheulean bifaces, variation of shape and size is pronounced and obvious” (Gowlett, 2006, p.203).

From the perspective of artefactual variation, understanding the underlying factors that drive the generation of variation at a microevolutionary level can be closely compared to the study of genetic mutation in biological sciences (Cavalli-Sforza and Feldman, 1981; Eerkens and Lipo, 2005). There is a multitude of mechanisms that cause artefactual variation including the intentional introduction of cultural variants, for example, in the case of ornamental elaborations of artefacts. In addition, researchers have adapted genetic drift models to material cultural evolution, illustrating that in the absence of social biases or other selection mechanisms, drift alone can create cultural macroscale changes and chronological historical patterns on the basis of incremental small-scale modifications over the repeated course of cultural transmission (Koerper and Stickel, 1980; Neiman, 1995; Shennan and Wilkinson, 2001; Bentley et al., 2004;

Kohler et al., 2004; Shennan, 2011). Therefore, study of microevolutionary processes can give conclusive answers on how individual-level processes can lead to population-level change (Bettinger and Eerkens, 1999; Mesoudi and O'Brien, 2009).

Importantly, the introduction of unintended copying errors (imperfect replication) during artefact manufacture can create new variation in material traditions (Clarke 1968, p. 161; Eerkens and Lipo 2005; Hamilton and Buchanan 2009). A combination of computational, archaeological and experimental research approaches to the study of microscale copying errors, also termed *cultural mutations*, have mainly focused on how the human perceptual system has limitations in perceiving size differences between objects (Eerkens, 2000; Eerkens and Lipo, 2005; Kempe et al., 2012). These cultural mutations become introduced because of perceptual constraints beyond which humans fail to visually discriminate microscopic imprecision between two differently sized objects, and instead identify these objects as identical (Eerkens and Bettinger, 2001). These microscale copying errors therefore give rise to non-perceptive microscopic variation during copying processes. The perceptual threshold below which humans fail to discriminate differences between the dimensional attributes (e.g., 'length') of objects is termed the *Weber fraction*, and has been established at a value of 3% (Eerkens, 2000, Eerkens and Bettinger, 2001). In other words, objects have to be more than 3% different in size for the humans to visually perceive the difference. Recent studies have provided a defined baseline model for comparing and studying patterns of size variation in the artefactual record (Eerkens 2000; Eerkens and Bettinger 2001; Eerkens and Lipo, 2005; Kempe et al. 2012).

Eerkens and Lipo (2005) and Kempe et al., (2012) applied the computer simulations concept of the Weber fraction to on the basis of an 'accumulated copying error' model (ACE), which was also utilized later by Hamilton and Buchanan (2009). In the ACE model, Lipo and Eerkens (2005) simulated the accumulative effect of copying errors on metric size measures with a pre-defined error rate of three percent along multiple generations of individuals in ten independent cultural transmission chains. The simulations illustrated that while between-chain variation became larger, there was no change in the overall mean size. Kempe et al. (2012) transmitted 2D photographic representations of an Acheulean handaxe tool between participants along multiple cultural transmission chains. Every participant was asked to copy the size of the previous participant’s (or ‘generation’s’) artefact image to the highest accuracy possible. The findings of experiment confirmed the ACE model’s predictions that between-chain variation in artefact size becomes exponentially larger over time as copying error compounds over the course of cultural transmission. Yet, the experimental results by Kempe et al. (2012) also suggested slightly different findings in respect to the mean values compared to Eerkens and Lipo’s (2005) computational simulation. Kempe et al.’s (2012) experimental investigation found that the mean size of artefacts can enlarge over the course of transmission if the original size of the artefact that participants are asked to accurately adjust in size is in fact larger than the size of the image that they were asked to copy.

Overall, it may be emphasized that size measures were of primary focus in these previous research approaches on the production of copying errors in artefact manufacturing processes. To date, no experimental study has actively investigated copying error in shape aspects of cultural artefacts. However, shape as opposed to just scale variability is gaining increasing focus in culture evolutionary models (e.g., Lycett and von Cramon-Taubadel, 2015) because shape may carry particular importance in evolution of material culture since it is associated with functional and aesthetic properties (e.g., Roche, 2005; Buchanan and Collard, 2010a; Winter-Liveneh et al., 2013). Shape may, therefore, also come under the effect of selection biases (Mesoudi and O’Brien, 2008a) and drift processes (Lycett, 2008) and therefore has strong explanatory power in regards to the factors that generate spatial and temporal trends in variation. Shape variation may, therefore, be especially relevant when considering alternative processes of artefact manufacture. In 1967, Deetz assumed that profoundly different methods of manual manufacture of artefacts may have potentially different impact on the production of copying errors, which ultimately would generate differing levels of variation. Deetz notes that ‘additive’ processes, as found in pottery and basketry, contain the specific characteristic that they enable the manufacturer to reverse copying error by removing and adding material as desired. Conversely, in ‘reductive’ manufacturing processes, which are predominantly applied to manufacturing flaked stone tools, copying errors are not readily reversible. Flaked stone tools are created by applying a hammerstone to the desired raw resource material, or *core*, where flakes of stone are systematically removed through direct percussion, a process called stone tool *knapping* or *invasive bifacial knapping* for bifacial stone tools, such as Acheulean handaxe tools (Schick and Toth, 1993; Whittaker, 1994; Gowlett, 2006). The reduction process differs from other manufacturing processes in the fundamental key aspect that if a flake that detaches from the core happens to be too large, it will be impossible to re-attach it and to remove it again to the desired proportion; thus, stone tool knapping is exclusively a subtractive process (Baumler, 1995). As a direct result of the reductive manufacturing process, copying errors are irreversible and become preserved in the material record. Deetz (1967) argued that because copying errors are preserved during reductive processes, variation in the reductive manufacturing processes should be emphasized more so than in additive processes.

Deetz' assumptions (1967) of the differential impact of contrasting manufacturing traditions on the generation of copying errors would be difficult to test in archaeological artefacts given the vastly different conditions under which the different types of artefacts are produced. For once, these different artefacts vary in the raw material that they are produced from (for example, stone versus clay) and this is faced with the problem that different raw materials may affect variation differently. Therefore, these varying conditions obscure the reliable testing of these predictions.

In this research study, an experimental approach was proposed that investigated the effects of reversible versus irreversible manufacturing processes on shape copying error within one experimental model. The laboratory context contained the advantage to control for a variety of these factors in a manner that their key distinctions, the presence of reversible versus irreversible manufacturing processes, were highlighted. In this study, the effects of copying error on shape manifestations were investigated in two separate experimental conditions, one simulating reversible ('additive-reductive') manufacturing processes and the other simulating irreversible ('reductive-only') conditions.

In the experiment, all participants were asked to copy the shape of a 'target form', in this case a flint Acheulean handaxe replica, as faithfully as possible using a standardised block of plasticine and a table knife. According to Deetz' assumptions (1967), the main prediction was that reductive manufacturing processes, where material can be removed but not added, would create an intrinsically higher rate in shape copying error compared to reversible 'additive' processes. Here, it was of particular interest to investigate statistical effects on shape morphology and to employ a transformed data set based on size-adjusted morphometric variables. It should be clarified that while previous research in this respect was aimed towards investigating the concept of copying errors and determining a baseline of copying error rate (Eerkens and Bettinger, 2001; Eerkens and Lipo, 2005; Kempe et al., 2012), this experiment was not targeted towards examining perceptual biases but focused on the presence of a *procedural* bias. Thus, this was achieved by testing whether one procedural manufacturing condition, like in the case of reductive-only manufacturing processes, created intrinsically higher rates of copying errors compared to additive-reductive processes.

3.2 Materials and methods

3.2.1 Participants

60 participants in total were recruited to take part in this experiment. The majority of the participants were postgraduate and undergraduate students who were tested in a laboratory on the campuses of Queen Mary, University of London, and the University of Kent. Of the participants, 30 were females (mean age = 26, SD = 5.4, age range: 18-44 years) and 30 males (mean age = 28, SD = 9.8, age range: 18-64 years). Every participant was compensated with £4.

There were equal numbers of females and males in each condition. An equal amount of females and males were assigned to each condition to control for potential sex-related visuo-spatial factors (see e.g., Wynn et al., 1996).

3.2.2 Materials

Participants were provided with a flint replica in the form of an Acheulean handaxe made from stone as the main copying target form. The target form replica was knapped by Dr. Stephen J. Lycett from flint stone retrieved from the Kent Coast, United Kingdom. The major dimensions for the flint target form can be viewed in Figure 3.1. All participants produced their replicas from standardised plasticine blocks that were equal in their proportions to control for potentially confounding effects resulting from heterogeneity in starting conditions. The standardised plasticine blocks were produced in plastic containers that measured 13.5cm in length, 8.7cm in width, and 4.5cm in depth. Plasticine was filled into the containers until the plasticine was level with the edge of the box opening and the surface of the block was pressed flat. Two layers of robust thin plastic sheet (~12.5μm) were placed into the empty containers so that the edges of the sheets could be pulled gently so as to allow easy removal of the plasticine blocks once the containers were filled (Figure 3.2). Participants applied a standard table knife (Wilkinson) to the block of plasticine to form the plasticine replicas. The knife consisted of one entire piece of stainless steel and contained a total mass of 40.93g. Various measurements of its morphological features are visualised in Figure 3.3.

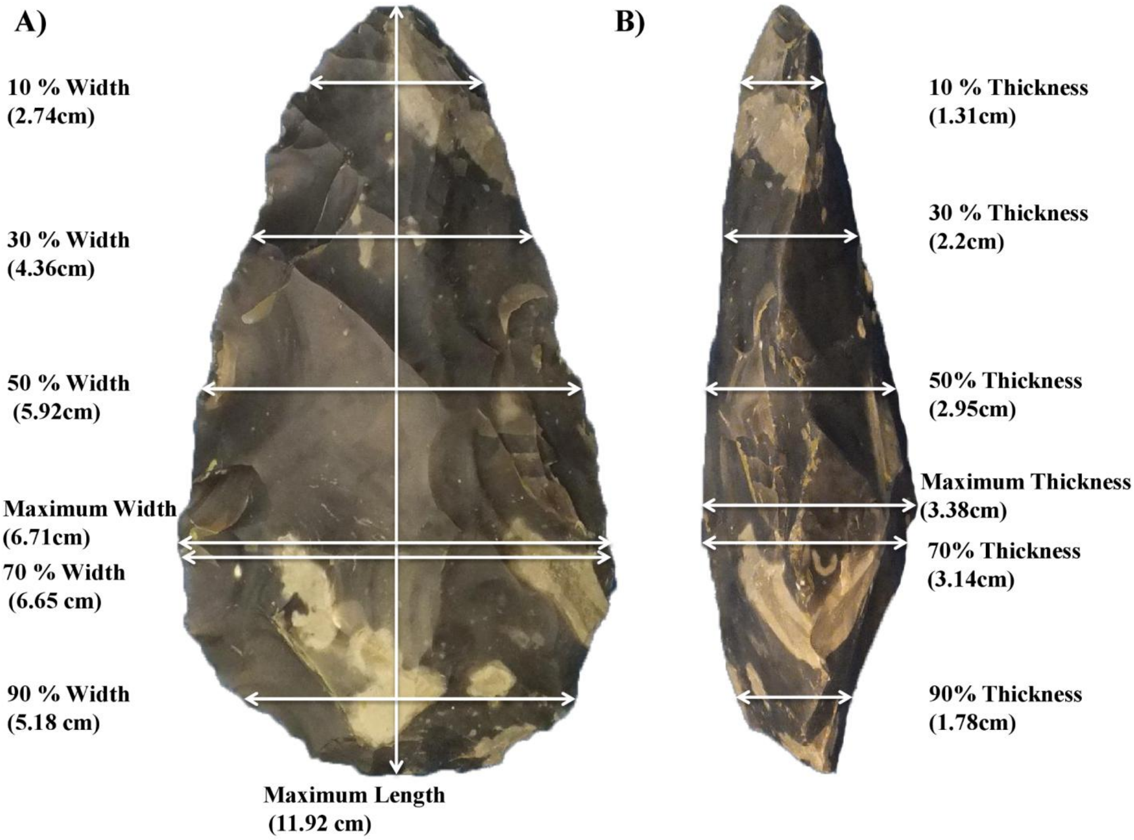

Figure 3.1: Flint handaxe replica used as the 'target model' during the experiment. Major dimensions are shown at various percentage points in plan-view (A) along the length (by orientation) line and profile-view (B).

Figure 3.2: The procedure of making standardised plasticine blocks using plastic containers that measured 13.5cm in length, 8.7cm in width, and 4.5cm in depth. Thin plastic sheets were placed inside the containers prior filling the plasticine to assure the gentle removal of the plasticine blocks.

3.2.3 Design and procedure

The experiment allows the incorporation of both reversible and irreversible manufacturing processes within one single experimental apparatus, with only the targeted procedural adaptations in each of two experimental conditions.

3.2.3.1 Condition 1 – The additive-reductive condition

This experimental task simulated manufacturing processes that were easily reversible. Therefore, participants were free to add or remove plasticine during the manufacture of their plasticine replica. This experimental condition was termed the *additive-reductive* condition.

3.2.3.2 Condition 2 – The reductive-only condition

The alternate experimental condition simulated reductive manufacturing processes as found in stone-tool knapping, and was termed the *reductive-only* condition. In the reductive-only condition participants were allowed to remove material from the plasticine block as desired; however, they were informed that they could not add plasticine onto their plasticine replica once material had been removed.

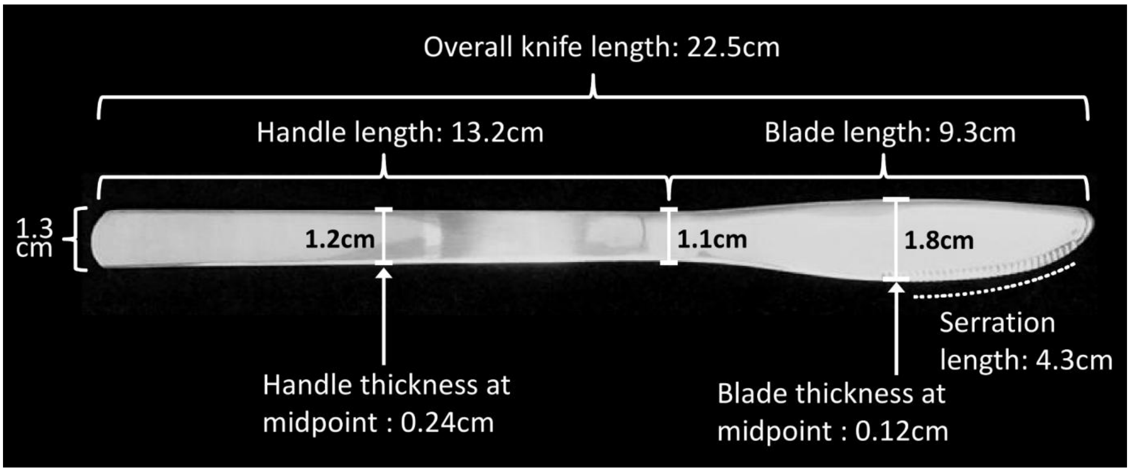

Figure 3.3: The stainless steel knife used by participants during the experiment in order to either remove or add material to their plasticine block.

The 60 participants were assigned to one of the two conditions so that there was an equal number of 30 participants in each condition. It has been demonstrated repeatedly that males appear to perform better in mental rotation tasks than females (Halpern, 2000; Linn and Peterson, 1986; Voyer et al., 1995). These differences may have played a role in the manufacture of material culture like stone tool artefacts especially in the more recent course of human evolution where sophisticated stone tool production was prominent (Wynn et al., 1996). Yet, sex differences in mental and spatial cognitive performance are not clear-cut, for example, in the case of mental rotation performances of 3D as opposed to 2D presentation, the effects between females and males are substantially decreased (Robert and Chevrier, 2003). To avoid potential confounding effects from sex differences, females and males were divided equally into each of the experimental conditions (there were 15 females and 15 males in each condition).It may be emphasised that the distribution of equal numbers of males and females within and between experimental conditions has been kept constant throughout all experiments in this thesis for the mentioned reasons. Also, the statistical analysis of shape copying error was undertaken on the group level, therefore, across populations of males and females. For these reasons, it was not necessary to test specifically for potential sex-related differences. Participants were assigned to one of the two conditions alternatively until the maximum number of males and females in each condition was reached. Participation in the experiment could not be repeated in the same or alternate condition. There were three left-handed participants in the additive-reductive condition and one left-handed participant in the reductive-only condition. The remaining participants were right-handed. A distribution of 10-13% of left-handed individuals in a population where the remainder is right-handed is representative of that of a general population (Toth, 1985a; Corballis, 1989; Raymond et al., 1996).

Participants were informed that the main task was to copy the *shape* of a target flint replica (Figure 3.1) as accurately as possible from one standardised block of plasticine and a simple steel table knife. Participants in each of the conditions were provided with one minute to handle and inspect the target replica from all sides and angles. While participants were encouraged to pay attention to the form and shape properties of the flint replica, they were explicitly instructed to prioritise copying the shape. When the one minute of examination time was over, participants were handed the steel knife and standardised block of plasticine and provided with 30 minutes to complete the copying task. All participants had only one attempt at the copying task although it should be emphasised that all participants completed the task within the time frame provided. The target replica remained with the participants throughout the experimental task and they were allowed to compare the target replica with their own copy from any side or angle and at any desired point during the experimental task, thus, memory effects were also carefully controlled for. Participants who relied on vision-corrective devices such as spectacles or contact lenses were allowed to wear these; therefore assuring that task performance was not affected by strong inconsistencies in visual capability. However, the application of external aids (scaled rules) that could improve the perceptual accuracy of the participants was not permitted. The photograph in Figure 3.4 shows a participant during the manufacture of her own plasticine replica during the shape copying task. Participants were reminded of the remaining time left to complete the copying task in five minute intervals.

Figure 3.4: Participant copies the shape of a target flint replica using a standardised plasticine block and a simple steel table knife.

3.2.4 Orientation protocol and morphometric analysis

Measurements were obtained for all replicas (including the flint replica target form) for 42 morphometric variables from the profile- and the plan-view perspective in digital format using a morphometric software tpsDig (version 2.16; Rohlf, 2010). The measurements were recorded by following the standardised orientation protocol as explicated in Chapter 2.

3.2.5 Compilation of shape error data set

To extrapolate the shape data, the raw measurement data set was size-adjusted via the method of calculating the geometric mean (e.g., Jungers et al., 1995). To begin the size-adjustment procedure, the geometric mean was calculated from the measurements for each replica separately. Then, size adjustment was completed when the measurement for each morphometric variable was divided by the geometric mean. In the next step of the analytical procedure, the copying error rate was extracted from the size-adjusted data set to facilitate the investigation of variation in shape morphology that arose during the copying task. The analysis was specifically tailored to compare population effects on shape manifestations of the design attributes in the two experimental conditions. The size-adjusted values of the 42 morphometric variables for the 60 replicas were subtracted from the equivalent 42 variables of the target flint replica. Then, a mean error was calculated for each of the 42 morphometric variables across the 30 replicas in each experimental condition separately. This generated two data sets comprising mean copying error in shape morphology for the 42 morphometric variables; one data set for each experimental condition.

3.2.6 Statistical analysis

Two separate sets of statistical analysis were employed to investigate differences in the rates of shape error produced between the experimental conditions. In a first analysis, the copying error rates in the reductive only condition and the additive-reductive condition were assessed for statistical significance by applying a Mann-Whitney *U* test. The copying error data sets did not pass tests of normality which justified the application of non-parametric tests. For the results, the asymptotic *p*-value as well as the Monte Carlo *p*-value (10,000 random assignments) were documented at $\alpha = 0.05$.

In a second statistical assessment, the geometric means of the replicas in the additive-reductive condition were compared against the geometric means of the replicas in the reductive-only condition for statistical significant difference. The analysis of the geometric means allowed an enhanced understanding whether participants made the replicas to a smaller or larger size in either of the two experimental conditions. This investigation on differences in the geometric mean values between the experimental conditions informed about a systematic directional size-related trend which could potentially be the result of removing larger amounts of plasticine in the reductive-only condition. A trend to make replicas smaller or larger could reveal an underlying strategy to correct for previous shape copying errors, for example. The geometric mean data were normally distributed and a two-tailed (asymptotic) t-test was employed at $\alpha = 0.05$. In addition, a Mann-Whitney *U* test analysis was also recorded to allow direct comparison between the analysis of the geometric mean data and that of the copying shape error. All statistical analyses were conducted in PAST v2.17 (Hammer et al., 2001).

3.3 Results

The first statistical analysis compared the rate of copying error of the reductive-only condition against the additive-reductive condition. The additive-reductive condition had a mean copying error rate of 0.115 (SD=0.04). The reductive-only condition had a mean copying error rate of 0.134 (SD=0.053). According to the Mann-Whitney *U* analysis, the copying error rate in the reductive-only condition was significantly different compared to the copying error rate in the additive-reductive condition (Mann-Whitney *U*-test: *U*=621.5, n_1=42, n_2=42, asymptotic p = 0.0191, Monte Carlo p = 0.0199). Thus, the first analysis showed that participants in the reductive-only condition engaged in overall higher shape copying error. Figure 3.5 demonstrates that the copying error rate in the reductive-only condition is much higher and also contains more overall variation. Mean shape error rates for each of the 42 morphometric variables can be viewed for both conditions separately in Figure 3.6 and Figure 3.7.

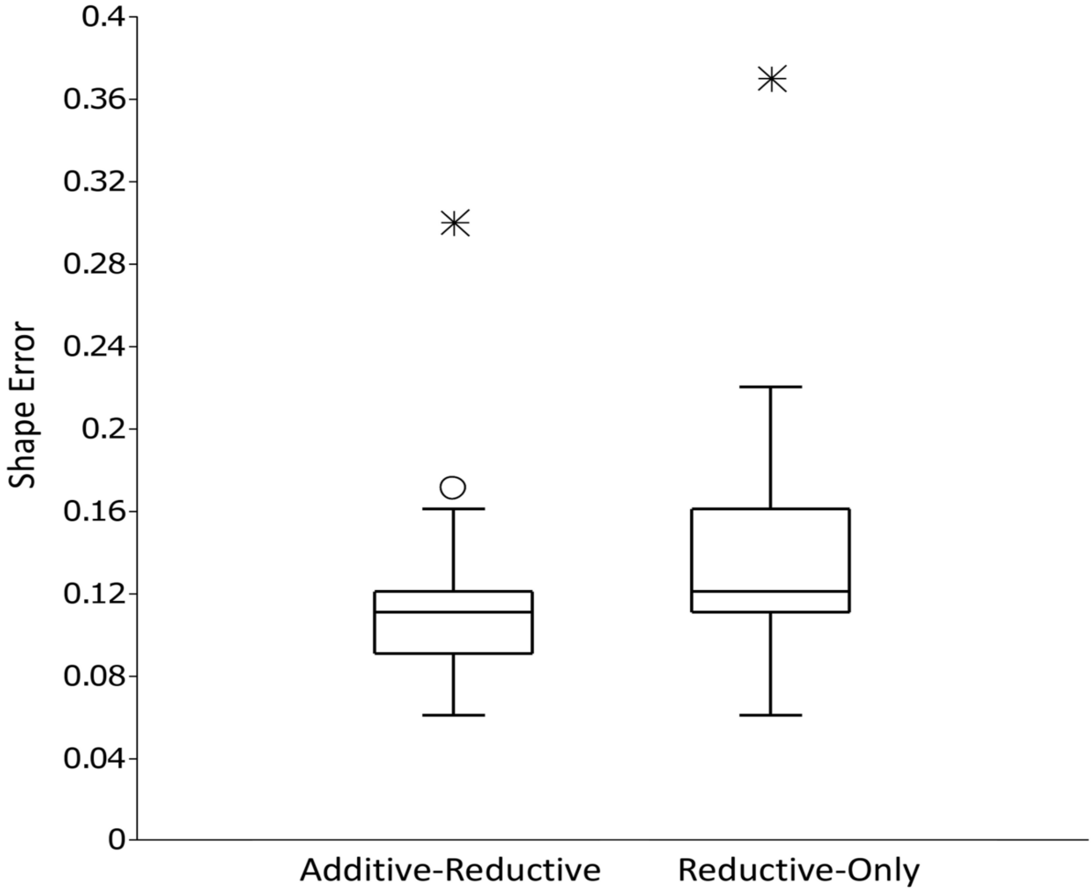

Figure 3.5: Box plots of overall shape error data in the experimental replicas for the ‘additive-reductive’ and ‘reductive-only’ condition. Medians are indicated by the horizontal lines across each 25-75 percentiles box. Whiskers mark largest data point ≤1.5 times box range. Outliers are marked by circles and extreme outliers are illustrated as stars.

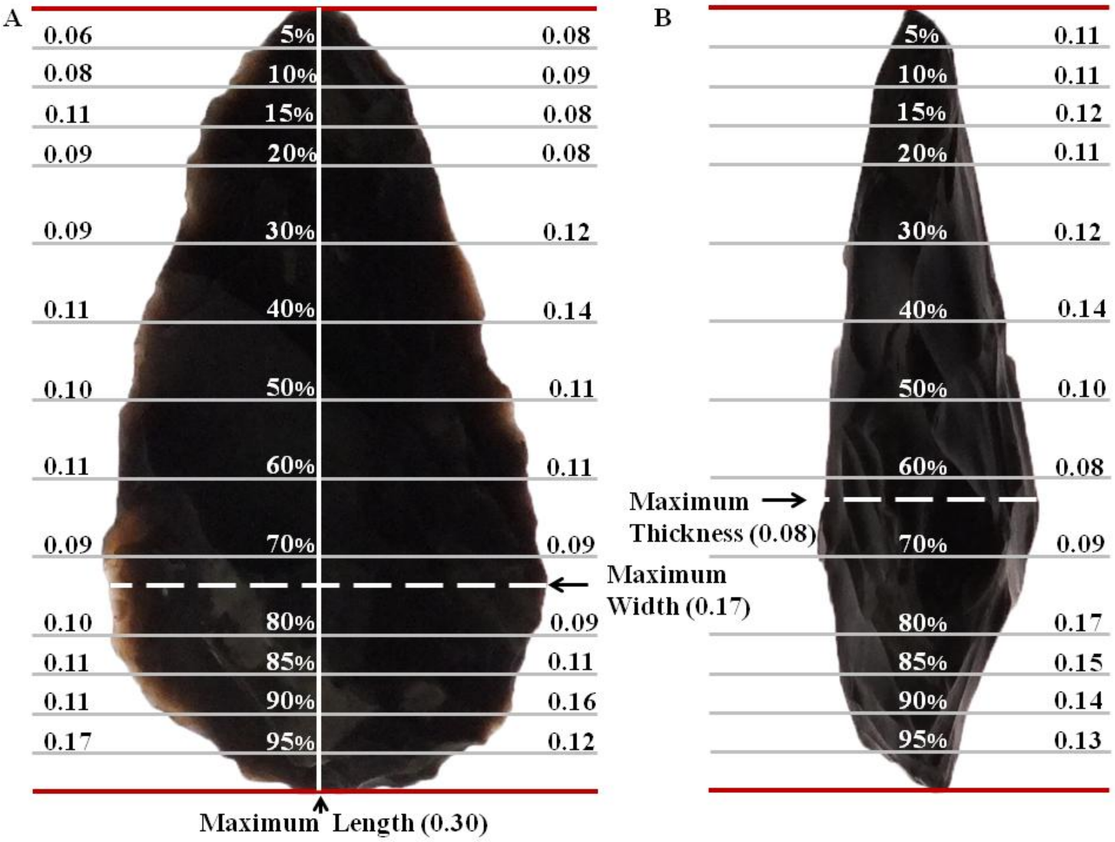

Figure 3.6: Mean shape error rates in the individual morphometric variables in the additive-reductive condition illustrated on the flint replica target form.

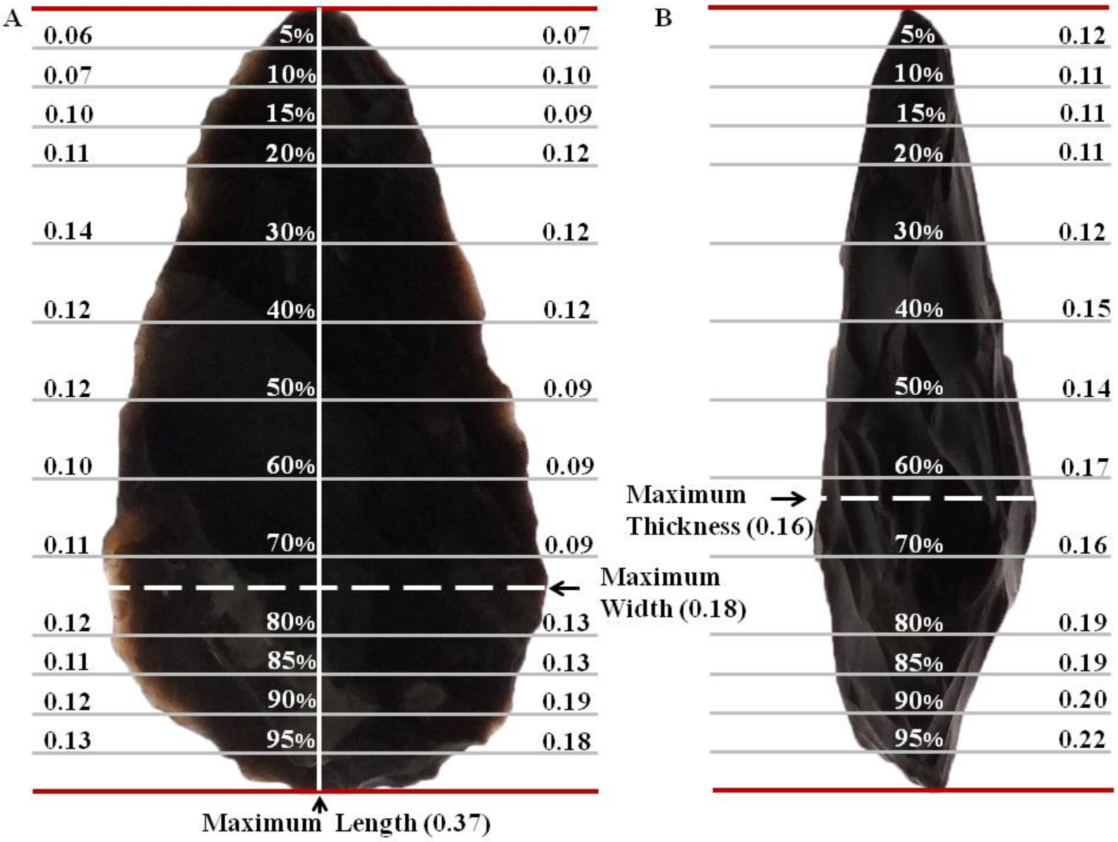

Figure 3.7: Mean shape error rates in the individual morphometric variables in the reductive-only condition.

The second analysis compared the sizes of the experimental replicas between the reductive-only and the additive-reductive conditions. The mean of the geometric mean data in the additive-reductive condition was 2.305 (SD=0.162), and the mean for the reductive-only condition was 2.350 (SD=0.265). Statistical comparison did not establish a significant difference in the size between the two conditions in the t-test analysis (n_1 = 30, n2 = 30, t (58) = 0.79316; asymptotic p = 0.432) or in the Mann Whitney U analysis (*U* = 410, n_1 = 30, n2 = 30, asymptotic p = 0.559, Monte Carlo p = 0.552). The results on the geometric mean data indicate that participants in the alternative conditions did not make their replicas systematically smaller or larger than participants in the alternate condition.

3.4 Discussion

Recent evolutionary approaches illustrate the importance of human copying errors in generating variation and macroscale change in artefactual traditions (Eerkens and Lipo, 2005). In the specific relation to stone tool knapping, Baumler (1995, p.12) confirms this notion that in the manufacture of stone tools “each removal is irrevocable and its consequences are permanent”. According to Deetz (1967), it is the factor of non-reversibility in processes like stone tool manufacture that causes greater variation as opposed to reversible manufacturing traditions, such as pottery or basketry, where copying errors can be undone through the reapplication of material. This study investigated the assumptions made by Deetz in a controlled laboratory context on the basis of statistically assessing copying error derived from morphometric shape data. In this experiment, participants took part in one of two experimental conditions. The first condition simulated the irreversible context (termed reductive-only condition) as found in stone tool knapping. The second condition simulated the reversible manufacturing context (termed additive-reductive condition) which is representative of manufacturing conditions such as pottery, basketry or weaving. In both physical manufacturing tasks participants copied the shape of a target Acheulean flint replica by using a steel table knife and a standardised block of plasticine. The resulting morphometric shape data were investigated in two separate statistical sets of analysis. One analysis illustrated that participants in the reductive-only condition produced statistically higher levels of shape copying error compared to the additive-reductive condition. The other statistical analysis demonstrated that a systematic trend to create experimental replicas to a larger or smaller size was not present in either condition. These result showed that the rate of shape copying error was statistically different; yet, this effect for shape variation was not driven by a statistically significant difference in size variation between conditions.

Altogether, these results confirm Deetz' assumption (1967) that irreversible manufacturing traditions create greater levels of copying errors in cultural artefacts, at least in terms of shape, than reversible manufacturing traditions. Considered from an evolutionary standpoint, it can be argued that shape features in cultural artefacts produced under irreversible manufacturing traditions produce higher cultural mutation rates than artefacts manufactured under reversible manufacturing traditions. Therefore, the rate of mutation in different manufacturing traditions is considerably affected by the process of production.

The results have a number of implications for the study of cultural traditions. Arguably, if these contrasting 'reductive' and 'additive' manufacturing traditions are of equal duration along a chronological timeline, the potential of evolutionary diversification would be greater for cultural artefacts produced in the reductive processes compared to those resulting from additive processes. This notion in regards to the 'ease' by which cultural traditions can change has also been referred to as 'evolvability' in biological terms (Ridley, 2004, p. 587). The results in this experiment indicate that the notion of evolvability should be considered in future research of cultural artefacts which span over similar time and special periods but nonetheless are the products of contrasting cultural manufacturing traditions. This may be important given that 'behavioural variability' has been proposed as a means by which key events in hominin behavioural evolution might be recognized (Shea, 2011).

This notion of evolvability leads to a further implication. Since irreversible, or 'reductive', processes underlie an increased mutation rate, cultural artefacts which are the product of these manufacturing traditions could be conceptualised as 'unstable'; this means that there is a tendency towards variation and diversification when stabilising mechanisms are not present. In this experiment, every morphological shape attribute was equal in fitness and did not pose a selective advantage over other morphological shape attributes. In other words, it was equally important to copy each shape component to the same extent. However, if stabilizing mechanisms were required to maintain specific shape components, for example on aesthetic and functional purposes, this would create a requirement to engage in “process controls” (Patten, 2005, p. 54-56; 2012). Process controls are manufacturing parameters or rules that a manufacturer employs to enhance the predictability and constancy of the end product towards the outcome desired, such as, for example, reliable replication. The supplementation of the Oldowan tradition, which did not describe a defined shape in the artefact technology (Toth, 1985b), with the industry of the Acheulean handaxe manufacture around 1.7 million years ago also marked the first occurrences of a purposeful imposition of predetermined shape (Roche, 2005). As noted previously, the Acheulean handaxe form was presumably selected for its functional utility in cutting and chopping activities as has been evidently demonstrated in a multitude of different scientific approaches (e.g., Bello et al., 2009; Domínguez-Rodrigo et al., 2001; Gowlett, 2006; Jones, 1980; Keeley, 1980; Roberts and Parfitt, 1999; Simão, 2002; Yravedra et al., 2010). If the form of Acheulean handaxes and concepts regarding the maintenance of their shape features were indeed culturally invoked, this would have also necessitated the introduction of process controls to accompany the transition from the Oldowan to the Acheulean stone tool technology. It has been further suggested that shape parameters, as in the case of stone tool projectile point traditions, were not only intentionally maintained but also adhered to during the course of resharpening which hints that process control must have been particularly developed in these cases (Patten, 2005).

Another associated implication is that for cultural artefacts produced as a result of reductive processes there is an enhanced risk for the manufacturer to engage in the production of copying error with each further step in the manufacturing process compared with corresponding steps undertaken to manufacture cultural artefacts that are the products of reversible processes. Baumler (1995, p. 12) clarifies that stone tool knappers have little choice but to remove further material if they aim to create a specific shape outcome. In this respect, when a knapper has to increase the numbers of production steps in the attempt to correct for shape copying errors, the likelihood of producing even more copying errors is also enhanced with each of these steps. In fact, while an obvious choice to maintain the considered shape outcome is to sacrifice size, this strategy has the potential to be disadvantageous in the particular instances where size has its own fitness values independently from shape, as could be possible in specific stone tools like Acheulean handaxes (Gowlett, 2006, 2009; Kempe et al., 2012). Since irreversible manufacturing traditions therefore come with costs attached to any additional procedural steps made, economisation of the number of procedural steps undertaken is beneficial in these circumstances, which would further encourage the introduction of process controls in irreversible manufacturing conditions.

To conclude, this experiment demonstrated that within one experimental context two contrasting manufacturing traditions created statistically different rates of copying errors. Specifically, the findings illustrated that cultural artefacts produced under irreversible manufacturing traditions contain higher mutation rates than alternative (reversible) manufacturing traditions. This has important implications for the evolvability of artefactual products created under these alternate traditions. The findings also imply an increasing need by our human ancestors to have implemented process controls in the manufacturing process in the era that marked the transition towards technologies where shape maintenance became increasingly prioritised, as was the case in the transformational stages from Oldowan to the Acheulean stone tool technology (Schick and Toth, 1993; Roche, 2005; Gowlett, 2006). The argument for the instigation of process controls is further encouraged by the pressure to economise the number of production steps undertaken, as every step in the production process carries a risk to engage in costly copying errors, which can only be amended by undertaking further material removal.

Chapter 4 - How do time constraints acting on manual manufacturing traditions affect artefactual variation?

4.1 Introduction

The study of the specific causal factors that generate variation during the manual manufacturing process (i.e., through the introduction of copying error, or what can be term 'cultural mutations') has received growing attention in the literature relating to traditions seen in material culture (Eerkens and Lipo, 2005, 2007; Hamilton and Buchanan, 2009; Kempe et al., 2012). There is growing acknowledgement in these research approaches that the study of variation-generating mechanisms can reveal important insights into the cultural evolution of material artefacts.

Previous work established that specific factors, such as motor, perceptive and memory constraints represent sources of such cultural mutations, yet, only rarely have these been investigated using explicit experimental frameworks (Eerkens, 2000; Kempe et al., 2012; Gandon et al., 2013, 2014). One such study by Eerkens (2000) tested empirically the effects of memory limitations on the generation of copying error introduced during the manufacture of 2D objects. In Eerkens' (2000) experiment, participants produced less copying error when they viewed a target form just before the copying task than when they purely relied on long-term memory. The study evidently showed that cultural mutations can occur as a result of memory effects and highlighted the importance of empirically testing the isolated sources of variation in manually manufactured artefacts. Kempe et al. (2012) demonstrated that copying errors accumulated exponentially over the course of multiple cultural transmission events and eventually generated detectable size variation over the long-term, as had been previously indicated by theoretical modelling and simulation (Lipo and Eerkens, 2005). Eerkens and Lipo (2005) and also Kempe et al., (2012) highlighted the importance of the further investigation of the effects of copying error since even undetectable levels of cultural mutations can generate trends and patterns of variations in cultural lineages in the long-term as these compound over the course of repeated cultural transmission.

Collectively, these experimental studies based on the empirical investigation of variation-generating mechanisms emphasize that important insights can be gained by investigating the cultural evolutionary processes acting on material artefacts. The experiment described in the previous chapter, which was conducted under controlled condition where a number of factors were held constant, illustrated that contrasting traditions of manual manufacture—such as reversible manufacturing traditions found in pottery or basketry as opposed to irreversible manufacturing traditions such as reductive stone knapping—can create, in statistical terms, significantly distinct rates of cultural mutation. The study emphasized that the controlled experimental study of parameters surrounding manual manufacture of material culture is paramount to understand specifically, and scientifically, the mechanisms that generate cultural mutations (i.e., copying error) and ultimately affect cultural evolution over the longer term.

One potential source of copying error that has not received much attention in the empirical research literature, however, is that of limitations, or ‘constraints’, on the manufacturing time available to produce material artefacts (i.e., time limit to complete a manufacturing task). While it can be intuitively assumed that constraints on the production time may have an impact on the generation of copying error, or rates of cultural mutation, the specific effect of time constraints on production time on variation is not currently known. This is despite growing attention regarding the importance of production time in regards to material culture, technological change and even tool variability (Rasic and Andrefsky, 2001). Torrence (1983) acknowledges that the production of manually manufactured tools requires a vast amount of time and energy and represents an important factor of material culture as a whole. As Torrence (1983, p. 12) states, “time available to complete a task … is a key variable in explaining differences in the structure of hunter-gatherer tool-kits as well as in patterns of procurement, manufacture and discard of artefacts”. This importance of studying time constraints has also been exemplified ethnographically in Binford’s (1978, 1979) research on Alaskan mobile foragers. He observed the hunting strategies of Nunamiut groups in north central Alaska who survive in extreme (cold) environmental conditions. He collected data on how the Nunamiut organised their time investment in daily activities, including hunting, craft activities (tool manufacture) and other subsistence-related activities (Binford, 1978). Nunamiut groups gain much of their protein from game hunting by awaiting crossing caribou herds, and it is important for Nunamiut mobile foragers to maximise their hunting efforts because the extreme environment they live in is otherwise heavily deprived of food resources (Binford, 1979). Yet, time availability for artefact production is a limited resource during hunting activities because of the additional time invested in anticipating the high mobility of these animals and the unpredictability of their occurrence. The planning of time invested in tool production is not only important for game hunting preparations. There is also a need to avoid a ‘time conflict’ between tool manufacture and the multiple other essential activities, such as eating, sleeping travelling, gathering raw resource material prior to tool production, and so forth. Binford (1978) observed conflicting conditions between the different subsistence activities, for example, if people invested more time in tool production, less time was spent on eating and socialising.

The Nunamiut provide an apposite anthropological example of how production time of material cultural artefacts is inevitably a resource that will be limited in the context of mobile foragers. Torrence (1983) referred to time constraints during hunting activities as ‘time stress’, leading to daily activities in the life of a mobile forager being carefully organised, or in other words, ‘budgeted’. Binford (1979) also acknowledged how tool manufacture required careful (i.e., in-advance) planning and preparation in order to be ‘geared up’ for these difficult game hunting conditions. One further strategy of dealing with such time pressures was to ‘stage’ tool manufacture into different phases, with manufacture taking place at different places and also at different times, and final tool production being executed at the hunting stands (Binford, 1978). Another form of economical scheduling of time resources was the “embedment of tool manufacture and maintenance into other subsistence strategies” (Torrence, 1983, p.12).

Insights by Torrence (1983) and Binford’s (1978, 1979) research on these ‘time constraints’ affecting tool manufacture have been further incorporated into computational simulation models that investigated the economic factors impacting technological change. The purpose of such models is to consider ‘costly’ technologies over ‘less costly’ alternatives in specific economic terms, such as whether certain technologies can be expected to make greater returns if more time is invested in their manufacture (e.g., Ugan et al., 2003; Bettinger et al., 2006). On behalf of such ecological foraging model, Bettinger et al. (2006) showed that two different technologies of distinct economical value can co-exist as they take up different foraging purposes. Californian Indians, for example, utilized a cheap and quickly produced ‘self bow’ for leisurely play and rough use. The self bow was still functional, however, as it was employed for “incidental, low payoff uses”, such as the hunting of small game (Bettinger et al., 2006, p.544). At the same time, they produced a more costly but also more effective ‘sinew backed bow’ which required longer production time but was utilized for most difficult game hunting events associated with higher returns (Bettinger et al., 2006, p. 544). What these models have in common is that the time spent in a tool production is acknowledged to be an important economical factor in tool manufacture.

There are additional ethnographic examples that demonstrate scenarios of how constraints on production time may arise during the manufacture of material culture. Such a circumstance can arise when ecological or economic circumstances require a tool manufacturer to produce a larger quantity of artefacts within the same timeframe, compared to previously smaller quantities of products. For example, research by Layton (2010) illustrated that family workshops in the Shandong Province of China, who specialised in wood block printing amongst other specialised crafts, endured an economic shift from craft to mass production during the course of the 20th century. Techniques for these crafts were traditionally transmitted within the family from parents to children via patrilineal descent. Initially, woodblock printing was a household-based production model run by the family workshops that produced prints for local demand. In more modern times (second half of the 20th century), higher quantities of woodblock printing products were manufactured for commercial purposes. In other words, such family workshops, which previously only supplied domestic and local demand, later faced production for an expanded clientele of tourists and more widely distributed clients. This constitutes an example of where an increase in production demand initiated an increase in the ‘time constraints’ on production time as greater artefact quantities had to be produced during restricted time availability.

These anthropological examples, and also the economical models by Bettinger et al. (2006) and Ugan et al. (2003), demonstrate that constraints on the production time are inherent parameters of material culture production. However, despite these anthropological examples demonstrating that time constraints on tool production are present the question of whether varying time constraints on tool production affect the generation of *variation* has not been addressed to date. This is the despite growing knowledge of the impact that mechanisms of variation, such as copying error, have on evolutionary change in material culture (e.g., Eerkens and Lipo, 2005, 2007; Kempe et al., 2012).

This study aims to investigate the effects of varying time ‘constraints’ on the production of copying error during the manual manufacture of cultural artefacts. An experimental approach is implemented with the aim to systematically test the effect of limits on the tool production time, therefore ‘time constraints’, on copying error in a laboratory context. One of the advantages of using experiments is the ability to provide specific answers as to whether differing time constraints (such as those seen in the ethnographic examples referred to earlier) can generate differing rates of cultural mutations. Moreover, time constraints are specifically tested on copying error related to the metric *shape* of the artefacts. Variation in artefact shape—as opposed to purely size variation—is a particularly vital parameter to consider in cultural evolutionary models (Lycett and von Cramon-Taubadel, 2015). Aspects of shape has been linked to functional and also aesthetic properties of cultural artefacts (Knecht, 1997; Roche, 2005; Gowlett, 2006; Winter-Livneh and Svoray, 2013), and may be subject to selective biases, but also stochastic drift-like processes (Lycett, 2008; Mesoudi and O’Brien, 2008a; Buchanan and Collard, 2010a). In addition, shape variation of artefacts has also been employed as a key variable in temporally and spatially relevant classification schemes (Trigger, 1989; O’Brien and Lyman, 2000). As previously mentioned, recent experimental and computational studies established that the accumulation of copying error can lead to detectable changes in size (i.e., ‘scaling’) parameters in artefacts during the course of long-term cultural transmission (Eerkens, 2000; Lipo and Eerkens, 2005; Kempe et al., 2012). These evolutionary mechanisms might equally affect shape variation but shape has received far less attention. The study of time constraints on artefact manufacture is, therefore, an ideal tool to understand the evolutionary mechanisms underlying shape variation in manufacturing traditions.

This experimental study aims to explore how time available to produce an artefact affect rates of shape copying errors by manipulating multiple varying ‘time constraints’ on the production time provided. In the experiment, participants copied a target form using a plastic knife and a standardised foam block. A total of 90 participants were divided into one of three ‘time conditions’ (i.e., varying limitations on the production time available): 20 minutes, 15 minutes or 10 minutes. One of the advantages of this experimental study design is that it can determine not only whether, but also how, rates of shape copying error alter when constraints on the production time periods are increased systematically. It might, for example, be reasonably hypothesized *a priori* that shape copying error varies proportionately and linearly with production time. That is, shape copying error rate may be lowest for the 20 minute time limit on production time, moderate for the 15 minute time limit, and highest for the 10 minute time limit, with statistically significant differences generated between the varying time limits. Alternatively, the rate of copying error may not vary proportionally and linearly with production time. Instead, a task specific 'threshold' might be the more appropriate manner to conceive of how time budgets affect mutation rates in manufacturing traditions. By testing a variety of different production time periods, the specific impact of time constraints can be investigated and understood more precisely in respect to whether, and when, rates of cultural mutations change significantly with respect to time constraints.

4.2 Methods and materials

4.2.1 Participants

A total of 90 participants were recruited at the University of Kent through a university advertising scheme. All participants in this study were tested in the same laboratory facility in the Anthropology Department. The participant cohort consisted of 45 females (mean age 23 =, SD = 4.14, age range = 18-44 years) and 45 males (mean age = 23, SD = 3.69, age range = 18-34 years). A reimbursement of £4 for was offered for their participation in the experiment. The data of thirty participants (15 females and 15 males) were re-utilised here for the 20 minute condition from the social learning experiment described in Chapter 5.

4.2.2 Materials

The target form chosen for this experiment was a foam model of an 'Acheulean handaxe' (Figure 4.1). The handaxe replicas were produced from the same foam material as the target handaxe, which is a form of dry floral foam. The floral foam is provided as machine pre-cut blocks of OASIS DRY SEC in a standardised format and measured 22.3×11×7.8cm. Since the foam material and plastic knife tool were previously described in Chapter 2, the descriptions are kept brief here. In many respects, the material was ideally suited for this experiment as it is a relatively stiff, robust material, which helped prevent any undesired modifications from simple handling, yet, it could be easily shaped by participants using every day cutting tools, thus exerting high control over the shaping process.

Figure 4.1: Experimental set-up for the shape copying task. Participants were provided with a target model, a standardised block of foam and a plastic knife to modify the foam during the copying task.

Participants were also provided with a simple plastic kitchen knife to remove and to modify the foam. Since the foam manipulation caused a certain amount of foam dust to disperse, participants were also provided with a lab coat to protect clothing, mouth protection and laboratory eye protection glasses. Participants were also provided with a countdown clock to trace the time left until task completion (it might be clarified that but participants were also reminded verbally of the remaining time to complete the copying task).

4.2.3 Experimental conditions and procedure

In this study, the main factor of manipulation was the time constraint under which the participants completed the copying of a target handaxe form. There were three experimental conditions that varied only in the time limit that participants had to produce the handaxe replicas. In one condition, participants were provided with 20 minutes to produce the handaxe replica. In the other two conditions, participants were required to complete the copying task in either 15 minutes or 10 minutes. All participants took part only once in the experiment and could not repeat the task in any of the other experimental conditions.

Participants were divided equally and randomly between conditions (n=30 for each condition). There were equal numbers of 15 females and 15 males in every condition, therefore controlling for visuo-spatial biases resulting from sex differences (e.g., Linn and Peterson, 1986; Voyer et al., 1995; Wynn et al., 1996; Halpern, 2000; Robert and Chevrier, 2003). The majority of participants were right-handed but there were also left-handed participants in each condition. There were four left-handed individuals in the 10 minute condition and three individuals in the 15 minute and 20 minute condition). Therefore, the distribution of left-handed (10-13%) and right-handed participants represented that of the general population (Toth, 1985a; Corballis, 1989; Raymond et al., 1996).

In the experiment, all 90 participants were allocated to one of the three experimental conditions alternatively and one participant was tested at a time. Participants in all three conditions were asked to copy the handaxe target form (Figure 4.2). The participants were instructed to consider the overall shape and form of the model target during the task, but were asked to specifically copy the model handaxe's *shape*. As an additional incentive to motivate participants, a £20 book voucher was offered to the individual who copied the target form most accurately (produced the replica with the least shape copying error) in addition to the £4 reimbursement. The instruction sheet for the 20 minute time condition can be viewed in Appendix A1.

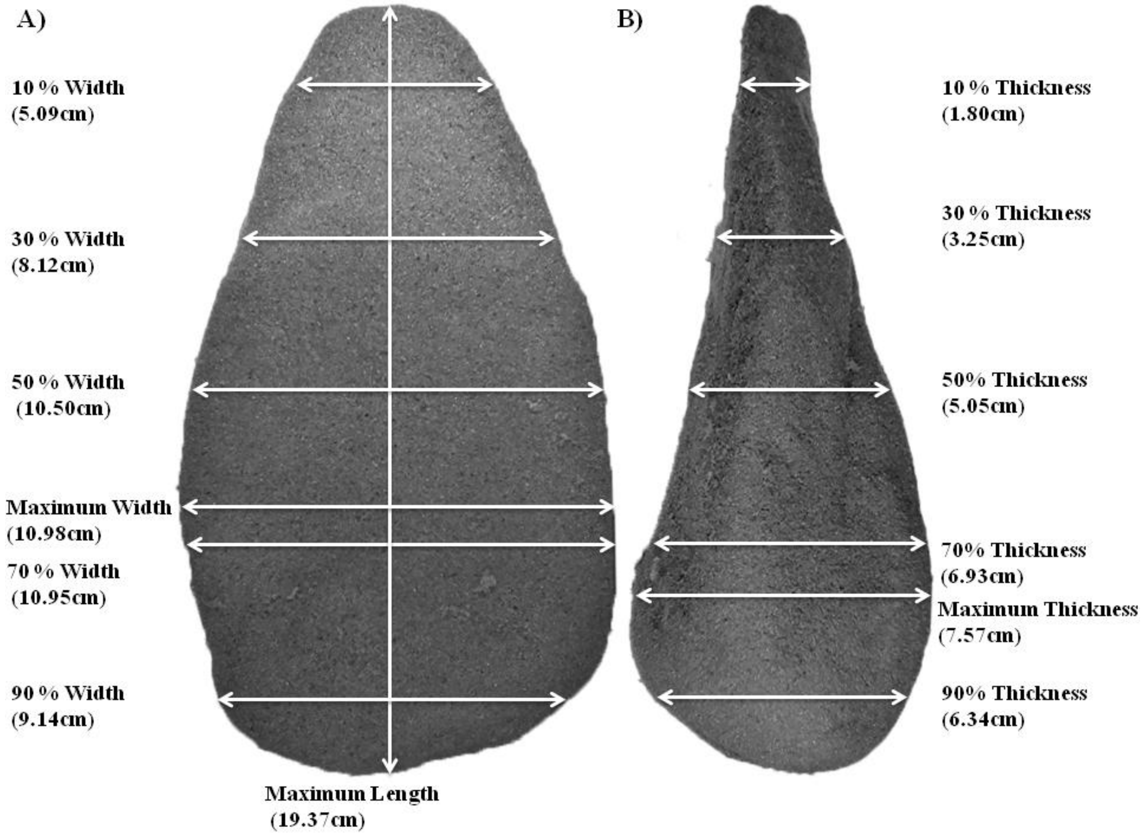

Figure 4.2: Foam' handaxe' replica used as the 'target form' during this experiment. Overall dimensions are recorded at various percentage points in plan-view along the length (by orientation) line (a) and profile-view (b).

Before beginning the experimental task, participants were asked to read the main instructions for the experimental task. Depending on which of the three conditions the participants were placed in, the instructions only differed in the production time provided to complete the copying task (20 minutes, 15 minutes or 10 minutes). Thereafter, they were provided with one minute to examine and handle the target handaxe from different sides prior beginning the copying task. Once the minute was over, the participants were placed at a table where the experimental task was conducted. All participants were provided with one standardised foam block and a plastic knife to do the manufacturing task.

To avoid memory-related confounding effects, participants were permitted to compare the target handaxe with their own replica throughout the experiment. Participants were verbally reminded in five-minute intervals of the time remaining to complete the task. In addition, participants were provided with a digital timer (which counted down the time left to complete the copying task) so they could check the remaining time at any point during the experiment. Participants had only one opportunity to take part and were not able to repeat the experiment in another condition. Figure 4.3 visually demonstrates a participant copying the target model in the laboratory.

Figure 4.3: Participant demonstrated the experimental context of copying the shape of a model target form using a standardised foam block and a plastic knife.

Descriptive statistics regarding the time spent in the manufacturing task are summarised in Table 4.1. Examination of the average times in each condition indicates that the mean times closely approach the maximum time provided in each condition. Therefore, the table shows that, on average, participants utilised the maximum time available in each of the three time conditions to complete the copying task, which confirms the validity of the experimental manipulation of the ‘time constraints’.

4.2.4 Morphometric procedures and compilation of the shape error data sets

All handaxe replicas produced in this experiment (including the foam target model) were oriented in the standardised format and underwent a set of digital measurements as explained previously in Chapter 2. Once the measurements were obtained, the raw measurement data sets were size-adjusted in the same principles as explained in Chapter 2. Shape error was calculated in the same fashion as explained in Chapter 3. Thus, the size-adjusted values of the 42 morphometric variables from each replica were subtracted from the equivalent values of the foam target model. Following the compilation of the shape error data sets, mean error values could be calculated for each morphometric variable across the 30 replicas in each of the three experimental conditions. Statistical comparisons were then undertaken on the mean shape copying error rates for the 42 morphometric variables between the experimental conditions.

4.2.5 Statistical analysis

The shape error data sets from the three time constraint conditions were compared using the non-parametric Kruskal-Wallis test, where $\alpha=0.05$. The conservative non-parametric analysis was applied since the shape error data were not normally distributed. Subsequently, a post-hoc analysis compared pairs of the different factor levels where both the uncorrected Mann-Whitney *U* tests (asymptotic) were reported which are considered valid in the face of a statistically significant Kruskal-Wallis test (Dytham, 2011), as well as the more conservative Bonferroni corrected p′ values, where $p' = pN_{\text{pairwise.}}$ All analyses were undertaken in PAST v2.17 (Hammer et al., 2001).

4.3 Results

In the 20 minute time condition, participants displayed a mean copying error of 0.137 (SD=0.047). For the 15 minute time condition an average shape copying error of 0.147 (SD=0.066) was recorded. Lastly, an average shape copying error rate of 0.173 (SD=0.067) was produced in the 10 minute time condition. These results regarding the mean shape error rates are visually illustrated in Figure 4.4.

According to the Kruskal-Wallis analysis, copy error rates were not significantly equal in all three conditions (H = 8.297, p = 0.015). The results of the post-hoc comparisons can be viewed in Table 4.2. The Mann-Whitney *U* analysis showed that there was no statistically significant difference in the rates of shape copying error between the 20 minute condition and the 15 minute condition. This was the case in both the uncorrected comparisons and the Bonferroni corrected comparisons. In addition, the uncorrected Mann-Whitney *U* test indicated a significant difference between the 20 minute and the 10 minute condition (*U* = 569, asymptotic p = 0.005) and also between the 15 minute and 10 minute conditions (*U* = 651, asymptotic p = 0.038). Although the latter result is not statistically significant when the Bonferroni correction is applied (p′ = 0.1161), there is still evidence of a significant difference between the 20 minute and the 10 minute condition with the Bonferroni correction (p′ = 0.0151). Individual mean shape error rates for the morphometric variables within each condition can be viewed in Figure 4.5, Figure 4.6 and Figure 4.7.

Table 4.1: Descriptive statistics of time spent on completing the manufacturing task.

	Time condition		
	10 min	**15 min**	**20 min**
Mean	9.96	14.9	19.24
SD	0.15	0.33	1.77
Minimum	9.4	13.56	13.03
Maximum	10	15	20

Descriptive statistics regarding the time spent in the manufacturing task are summarised in Table 4.1. On average, participants utilised the maximum timeframe available in each of the three time conditions to complete the copying task.

Table 4.2: Mann-Whitney *U* comparisons following Kruskal-Wallis test (H = 8.297, p = 0.015). Upper right diagonal = uncorrected (asymptotic) p values, lower left diagonal = Bonferroni corrected p′ values, where $p' = pN_{pairwise.}$

	20 min	**15 min**	**10 min**
20 min	–	0.5867	**0.0050**
15 min	1	–	**0.0387**
10 min	**0.0151**	0.1161	–

Overall, the statistical analysis on the rates of shape copying error in three time conditions illustrated that there was no statistically significant differences between the 20 minute condition and the 15 minute condition. Only when time constraints were reduced to 10 minutes (i.e., 50% of maximum) did a statistically significant difference occur between the time conditions. The results support the main prediction of the study that increasing time ‘stress’ or ‘constraint’ on the manual manufacture of experimental handaxe replicas lead to a statistically significant increase in shape variation (i.e., cultural mutation rate). Hence, at least in statistical terms, shape copying error generated during manual manufacture in these experiments changed in a fashion most plausibly explained by the effect of reaching a ‘threshold’.

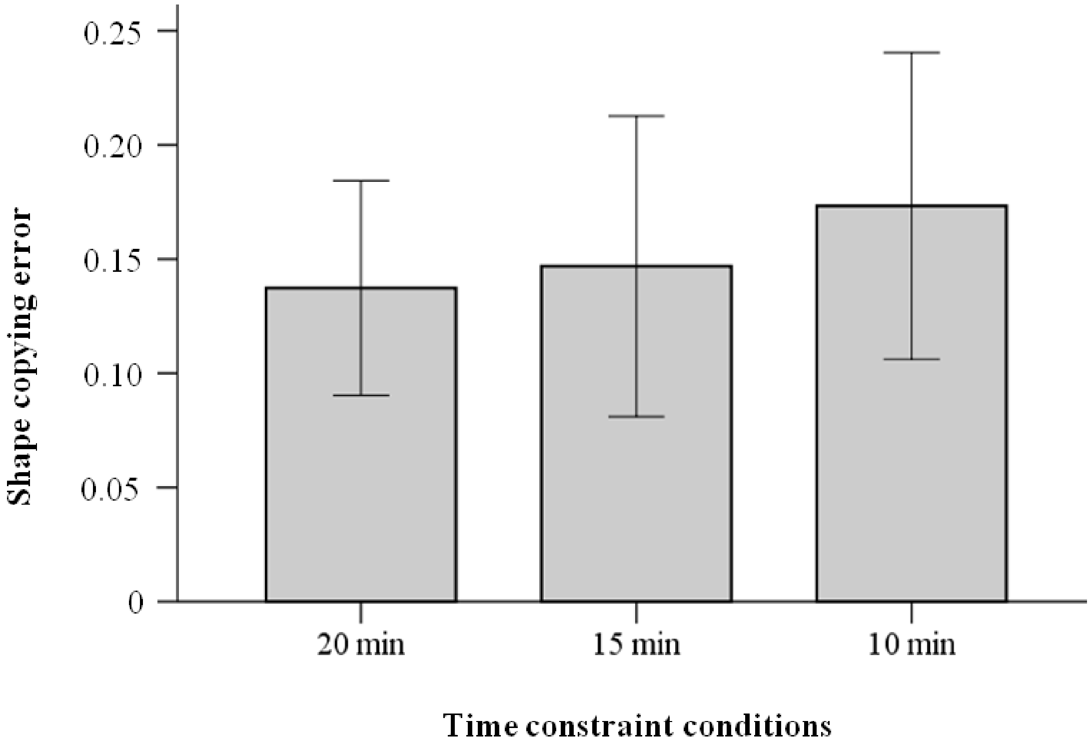

Figure 4.4: Mean shape error (bars) in the different time constraint conditions. Whiskers show standard deviations (one sigma).

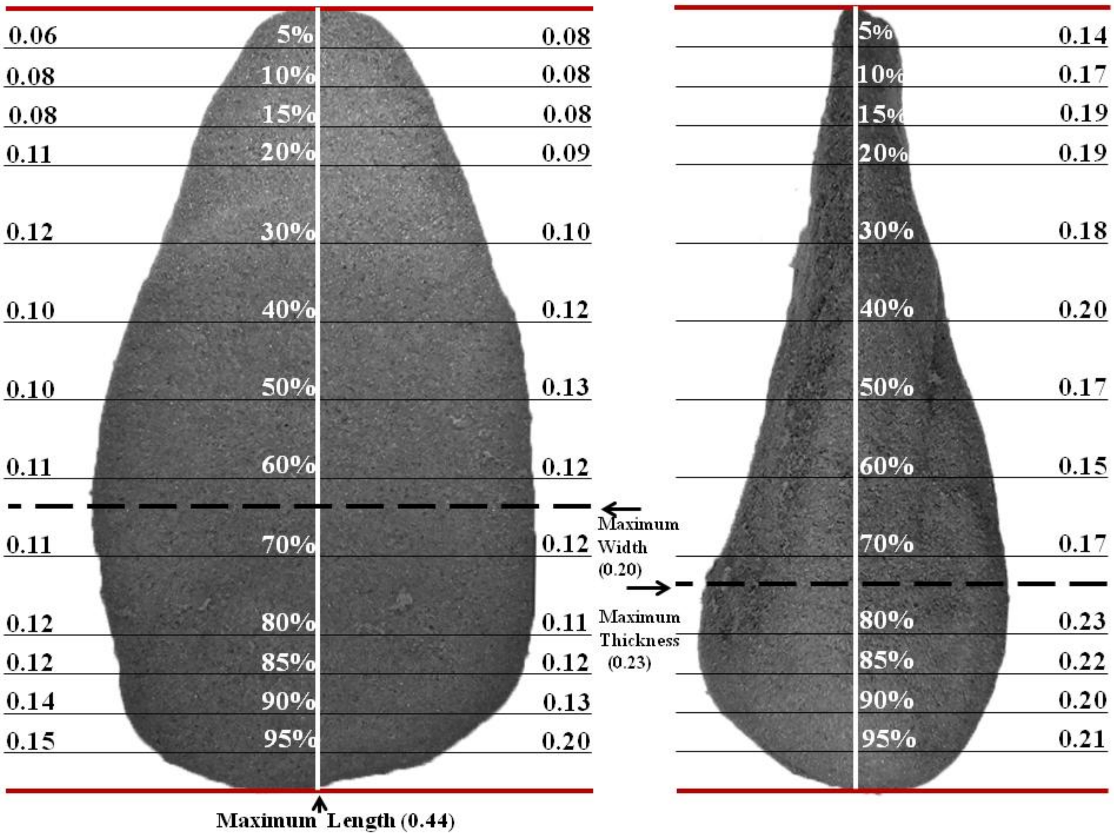

Figure 4.5: Mean shape error levels in the 20 minute time condition for each of the 42 variables.

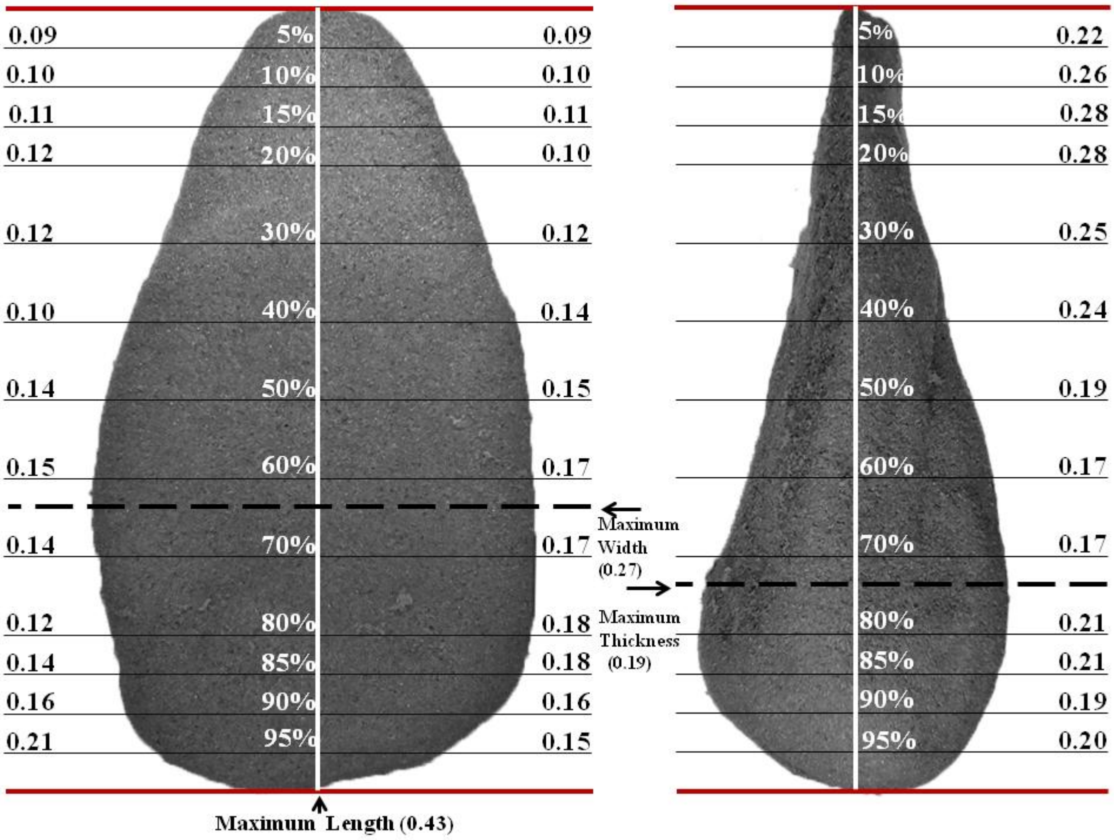

Figure 4.6: Mean shape error levels in the 15 minute time condition for each of the 42 variables.

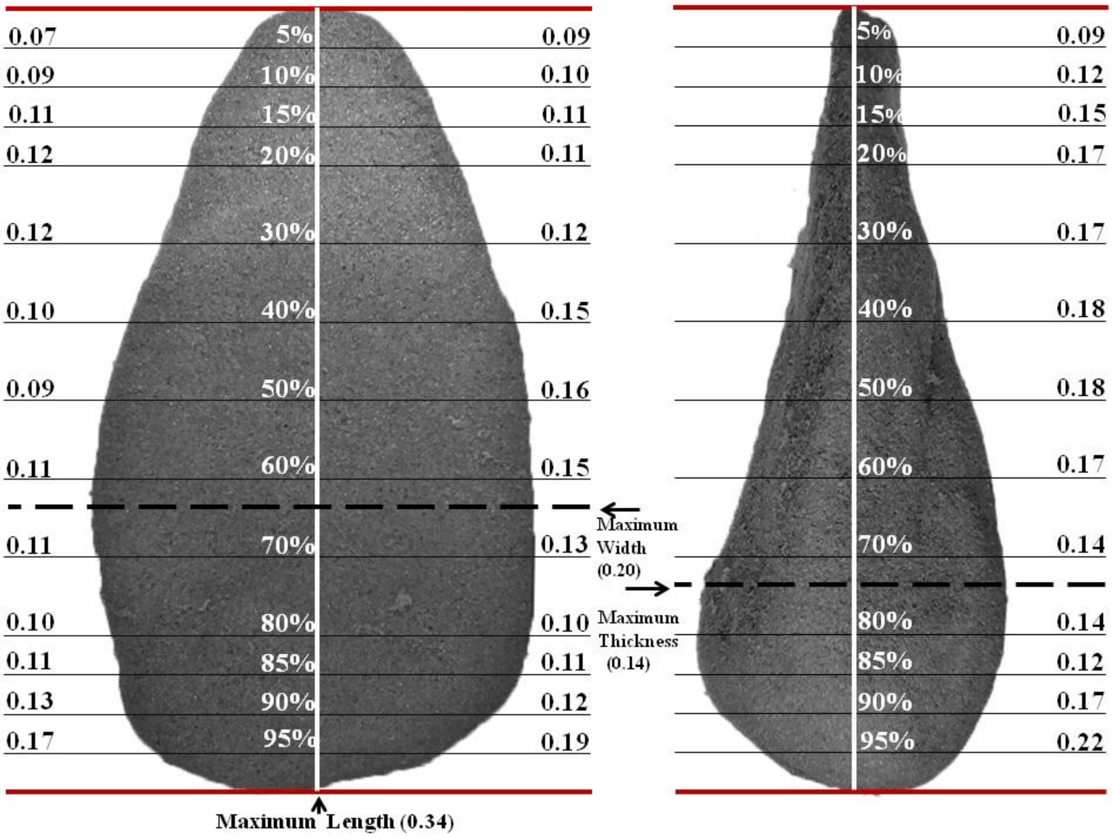

Figure 4.7: Mean shape error levels in the 20 minute time condition for each of the 42 variables.

4.4 Discussion

Ethnographic and computational research on mobile forager societies indicate that the time invested in manual tool production is a vital aspect of hunter-gatherer economy (Torrence, 1983; Rasic and Andrefsky, 2001; Ugan et al., 2003; Bettinger et al., 2006). In fact, anthropological examples of Nunamiut mobile foragers described by Binford (1978, 1979) illustrates that the presence of a range of subsistence activities as well as unpredictable ecological factors generate 'constraints' on the time available for tool manufacture. Nunamiut foragers have created subsistence strategies to accommodate such constraints, for example, by carefully 'budgeting' time for tool production (Torrence, 1983). However, constraints on tool production time can also arise from an alternate anthropological context where manufacturers are faced with the pressure of producing higher quantities of artefacts under limited time availability due to changing economic demands. The possibility that a manufacturer has to increase the number of artefacts in a shorter timeframe due to changing market demands is also supported ethnographically. In the case of Chinese family workshops who specialise in woodblock printing, families experienced an 'economic switch' from traditional domestic craft production to mass production of woodblock printed posters in the 20th century (Layton, 2010). These family workshops that originally produced for local trade and demand were later faced with the increased production of artefactual quantities to satisfy expanding demand. Therefore, a variety of anthropological examples indicate possible scenarios of 'time constraints' acting on the production of material culture.

This experiment specifically focused on the effect of 'time constraints' during manual manufacture on artefactual *shape variation*. This effort to study variation-generating mechanisms is based on recent empirical and computational research studies, which illustrate the importance of the study of variation to enhance our understanding of the mechanisms underlying cultural change and evolution (Eerkens, 2000; Kempe et al., 2012). There is growing knowledge that one source of variation, in the form of small copying errors, can be introduced during the manual manufacturing process of cultural artefacts, generating between-assemblage variation and potentially leading to visible change over the course of cultural transmission events (Lipo and Eerkens, 2005; Kempe et al., 2012). One experimental example (Chapter 3) which focused on manual manufacture specifically, demonstrated that different traditions of manual manufacture can generate significantly different rates of cultural mutations during the production of cultural artefacts. This indicates that this notion of time constraints may be an important (yet under-studied) variable that needs to be given greater consideration in cultural evolutionary models. Indeed, since production time is a vital proponent of manually produced material culture, it is imperative to understand the impact of such time constraints on variation during the manual manufacture of artefacts, especially in terms of potential impacts on cultural 'mutation' rates.

Here, an experimental model was proposed to systematically test the effects of gradually increasing time constraints on shape copying error during the production of experimentally produced foam 'handaxe' artefacts. In the experiment, all participants were asked to faithfully copy a model 'handaxe' target form. In three experimental conditions, the production time was limited either to 20 minutes, 15 minutes, or 10 minutes. Thus, time constraints were increased by shortening the production time systematically by 5 minutes. Overall, the results showed that when time constraints were altered by the same amount across conditions, mean levels of shape copying error increased. However, this increase was not sufficient to generate statistical significant differences between the 20 minute and the 15 minute time conditions. Only when production time was reduced to 10 minutes (i.e., 50% of maximum) did statistical significance emerge between the time conditions. In this task, the results provided statistical verification of one part of the hypothesis, which specified that with gradually shorter production time there was a significant increase in shape copying error. The fact that significance levels in this experiment were primarily driven by a sharp increase in shape copying error in the 10 minute condition indicates that, in the 10 minute time condition, a 'critical' point was reached where a high accuracy in the copying of manual artefact was no longer achievable, leading to a sharp increase in copying error, at least when compared to accuracy levels obtained when participants had 20 minutes to complete the task.

Ultimately, these results are important since part of the purpose of this study was to determine whether shape error rates changed proportionally across all conditions, or whether the concept of a task specific 'threshold' is the more appropriately manner to conceive the effect of time budgets on mutation rates in manual manufacturing traditions. While the results in this task support the overall premise that decreasing time budgets will lead to an increase in shape copying error, the results more strongly support the notion that shape copy error is best modelled according to a ‘threshold’ effect, beyond which mutation rates increase more sharply. In this experiment, this threshold fell somewhere between 15 minutes and 10 minutes, although the threshold may vary depending on the task. In addition, regarding the question whether or not shape error increases linearly once such threshold is reached may be investigated more specifically by future research. Therefore, future experimental research could help focus more specifically on the area surrounding the critical point (such as around the time points of 8 minutes, 10 minutes, or 12 minutes).

Overall, a deeper insight was gained from these findings that illustrated exactly *how* increasing time constraints affected shape copying error when other factors were controlled for. One of the important findings of this study is that time constraints on the manual production of material artefacts can generate statistically significant levels of shape variation. For the first time, evidence has been gathered that supports the notion that higher rates of cultural mutations are likely to occur as a direct result of imposed ‘constraints’ on artefactual production time. It can therefore not be discounted the possibility that time pressures on the manual manufacture of cultural artefact are influencing artefactual variation. What these results also imply in evolutionary terms, therefore, is that in addition to these aspects, detectable changes (trends that take effect on the population-level) in artefactual patterns of spatial-temporal variability may also reflect differing or changing production-time budgets. In fact, these production-time budgets may themselves underlie processes of selection and cultural drift. Hence, ‘time-budgeting’ factors may need to be given greater consideration in evolutionary models of material culture change.

In addition, when regarding how cultural factors may link to such results, one possible implication may be that ‘costs’ related to highly increased mutation rates beyond such ‘threshold’, may drive a pressure to find cultural means of maximally ‘economising’ production time. This is because such high mutation rates beyond such a ‘threshold’ contain the potential to ‘disintegrate’ cultural traditions over the course of cultural transmission. One possible and worthy future investigation in respect might be the extent to which distinct production stages, or components, of manual manufacture hold their own ‘time budgets’. In other words, where it was described earlier that hunter-gatherer societies compensate for time constraints acting on various subsistence strategies by implementing ‘time budgeting’ strategies (Binford, 1978, 1979; Torrence, 1983), the same notion of ‘time budgeting’ may be applicable to the different production stages of the manufacturing process. Examples of material culture with a prevalence of multiple conceptual and practical distinct stages in the artefactual production are widely known, for example, in the context of the manufacture of pottery (e.g., Randall-MacIver, 1905; Smith, 1978; Orton et al., 1993, p.113-131), basketry (Weltfish, 1932, p. 108/109); stone tool knapping (Roche, 2005) and textile production (e.g., O’Neale, 1947). Dynamic ‘time scheduling’ has been described by Torrence as “division of time into small parcels which are then juggled according to some set of priorities” (Torrence, 1983, p.12). There may be a dynamic where such segmented time budgets can be rearranged under varying time constraints in order to strategically optimise such production time so that copying error remains low under imposed ‘time constraints’. In the context of artefactual production where the priority is to keep copying error rate low under varying degrees of time constraints, such prospective rearrangement of the ‘time slots’ allocated to manufacture itself may become one possible strategy where different ‘components’ of the manufacturing processes are *distinctively* affected by copying error. In other words, ‘simpler’ as opposed to more ‘difficult’ components of the manufacturing process may be distinctively affected by copying error. As one possible solution to the optimisation of time stress, such ‘simpler’ production phases could be ‘sped up’ in a fashion whereby shape accuracy can be maintained. Future experimental research may beneficially be applied to evaluate the effect of differing time budgets on copy-error rates in these terms, and so evaluate these contentions. It may be worth mentioning that future research may attempt to investigate a greater number of time constraints in a different experimental task, so as to examine whether variation under a greater number of time constraints describes a more linear pattern.

To conclude, this experimental research in this chapter has explicated that varying time constraints can distinctively affect shape error rates at statistically significant levels. In this experiment, 90 participants were provided with 20minutes, 15minutes, or 10 minutes to produce a foam replica. While mean error increased when the time provided to produce cultural artefacts was reduced, significant differences were only obtained once production time was reduced to 10 minutes. These results support the hypothesis that the effects of time constraints acting on shape error rates are best conceived as behaving according to a ‘threshold effect’, beyond which there is a sharp increase in cultural mutation rates. These findings suggest that ‘time budgets’ available to production time in the prehistoric past may have facilitated distinct levels of shape variation that can be measured in spatial and temporal patterns of variation. It is further implied that ‘time budgeting’ factors require further investigation in cultural evolutionary models concerned with cultural change in material culture. Finally, and also keeping the previous discussion point in mind, these results reiterate the importance of using experimental approaches to understand the underlying causes of distinctively varying cultural mutation rates in artefactual products (Eerkens, 2000; Kempe et al., 2012; Schillinger et al., 2014). Equally, the time provided to participants in order to complete the task conditions is a factor that will also need to be taken into account in future experimental work of this type.

Chapter 5 - The impact of imitative versus emulative learning mechanisms on artefactual variation: implications for the evolution of material culture

5.1 Introduction

Models of cultural evolution highlight the importance of understanding the multifarious compounds of social mechanisms that underlie historic trends in human technological change (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985; Henrich and McElreath, 2003). Recently, computational and ethnographic population-based models have considered how evolutionary dynamics such as biased transmission and unbiased transmission mechanisms (such as drift), pattern variation that lead to detectable trends on the macroevolutionary level in the archaeological record (Neiman, 1995; Kohler et al., 2004). Recent advances in the study of the effects of social biases, and their effects on macro-evolutionary patterns of variation, have promoted the idea that biased cultural transmission affects patterns of variation differently from unbiased transmission events. This has led to the utilisation of neutral variation as a baseline, or 'null model' (Neiman, 1995; Shennan and Wilkinson, 2001; Bentley and Shennan, 2003; Bentley et al., 2004, 2007; Kohler et al., 2004; Mesoudi and Lycett, 2009; Shennan, 2011).

These computational models and macroevolutionary approaches to the study of cultural transmission have recently been extended to the study of individual-level mechanisms that elucidate how variation on the small-scale level explains trends at the population level. One of the more recent contributions is the accumulated copying error model (ACE) (Eerkens and Lipo, 2005; Kempe et al., 2012) explained previously in Chapters 1 and 3. The predominant contribution of the ACE model is that it explains how unintentional copying errors, or cultural mutations, create patterns of variation that lead to detectable changes over the course of cultural transmission (Eerkens and Lipo, 2005; Kempe et al., 2012). The model also highlights that the empirical study of small copying error is a useful tool to uncover the influence of social processes on patterns of variation. Eerkens and Lipo (2005) applied the ACE model to Rose Spring Projectile Points from Owens Valley (USA). They found that some attributes (such as thickness) did indeed fit the ACE predictions of neutral variation but they also discovered that the basal width displayed decreased levels of variation compared to neutral expectations. Therefore, some social processes (i.e., conformity) might have been at work to counter-act the generation of variation based on 'cultural mutations'. Similarly, Kempe et al. (2012) applied the ACE model to morphological data retrieved from 2601 Acheulean handaxes, again showing that morphological variation was lower than predicted by the accumulated copying error model, thus, emphasizing that other processes may have implicated the decrease in variation.

Few ethnographic and experimental approaches to date have actively researched the impact of social learning mechanisms on patterns of variation in the archaeological record (Mesoudi and O'Brien, 2009). One study by Bettinger and Eerkens (1999) elucidates how distinct individual-level social processes generate and affect variation differently in separate populations of projectile points. Their study illustrated that high morphological correlation between attributes of point artefacts in central Nevada were the result of an 'indirect bias', where successful or prestigious models' whole artefact forms were copied. The fact that the indirect bias described the 'complete' acquisition of the artefact form also explained the strong correlation between attributes. Conversely, poor morphological correlation between Great Basin projectile point attributes manufactured in eastern California was attributed to a transmission process called 'guided variation', where only a fraction of cultural variants was copied and a larger part of additional trial-and-error modifications was employed. In addition to this approach, an experimental study by Mesoudi and O'Brien (2008a) further illuminated the importance of the study of 'social learning' as opposed to 'individual learning' mechanisms underlying such biases and their effects on patterns and trends in artefactual evolution (Mesoudi and O'Brien, 2008a). Social learning is defined as the non-genetic transmission of cultural variants between individuals by means of observational learning from others (Boyd and Richerson, 1985). Individual learning is a non-social process whereby an individual learns to achieve a goal by trial-and-error. Mesoudi and O'Brien (2008a) empirically tested the effects of cultural (social) versus individual learning in a virtual hunting game context where participants built their own digital arrowhead on the basis of a variety of continuous and discrete attributes. In a virtual game environment where hunting success depended on the compositional nature of the arrowheads, the study provided experimental support for Bettinger and Eerkens'

(1999) hypothesis, by showing that experimentally-induced indirect bias (the copying of successful group members' virtual arrowheads) generated high inter-attribute correlations resembling prehistoric Nevada, while experimentally-induced guided variation (social learning followed by individual trial-and-error) generated lower inter-attribute correlations resembling prehistoric California. Bettinger and Eerkens (1999) and Mesoudi and O'Brien (2008a) have made an important contribution to material cultural evolution by illustrating how individual-level social transmission mechanisms can generate detectable macroevolutionary changes in artefactual culture (Eerkens and Lipo, 2005; Mesoudi et al., 2006b).

One aspect of cultural evolution models is to understand how social learning can explain lasting stable trends in the artefactual record, which draws the focus on social learning mechanisms as forms of 'cultural inheritance' (Boyd and Richerson, 1985). The study of the specific social learning mechanisms that can explain the perpetuation of distinct cultural variants has been undertaken predominantly within the field of comparative psychology (Whiten and Mesoudi, 2008; Galef, 2012). Comparative psychology comprises the study of behaviours and social processes in non-human animal species, partly also to enhance the understanding of human behaviour and its evolution (Whiten et al., 2009a; Heyes, 2012; Dean et al., 2014). Some of the most convincing evidence on social learning within the animal kingdom has been derived from controlled experimental approaches on tool-use in chimpanzees (*Pan troglodytes*). For instance, separate captive groups of chimpanzee have been shown to pass on distinct multi-action tool-use techniques along multiple simulated generations at high copying fidelity, after the initial model was removed (Horner et al., 2006). The study lent support to the notion that social learning processes alone can lead to the perpetuation of separate stable behavioural 'traditions' over the course of long-term cultural transmission (Whiten et al., 2005, 2009b). Inevitably, unravelling the past through comparative research on social learning mechanisms allows us to draw a common base with our previous ancestors in a sense that commonly shared, or 'homologous', cultural trajectories may have shaped evolutionary manifestations in the earliest of prehistoric cultural artefacts in the archaeological record (Russon, 1998; McGrew, 1992; Strier, 2001; Biro et al., 2003; van Schaik et al., 2003; Whiten et al., 2004; Herrmann et al., 2007; Lycett et al., 2007; Whiten et al., 2009a; Gowlett, 2009; Vaesen, 2012). Therefore, studies from the comparative realm increasingly illustrate that various forms of social learning mechanisms may have encompassed the social context of human ancestors (Lycett et al., 2009; Whiten et al., 2009a, b). In fact, there have been advances as well as ongoing debates concerning ‘how’ and ‘which’ social learning mechanisms generate distinct patterns of variation that can explain the persistence of cultural traditions (McElreath, 2000; Henrich and McElreath, 2003; Laland, 2004; Matthews et al., 2010; Slagsvold and Wiebe, 2011; Nielsen et al., 2012). In this respect, definitions of distinct social learning mechanisms have been promoted on the basis of the extensive studies within the animal kingdom (Fisher and Hinde, 1949; Galef, 1992; McQuoid and Galef, 1993; Heyes, 1994; Visalberghi and Fragaszy, 2002; van Schaik et al., 2003; Whiten et al., 2003; Boesch, 2003; Whiten et al., 2004; Galloway et al., 2005; Hopper et al., 2007; Hoppitt and Laland, 2008; Thornton and Raihani, 2010; Laland and Webster, 2011; Galef, 2012; Zentall, 2012).

Some forms of such social learning (Table 5.1) more specifically denote the precise mechanisms by which one in individual ‘copies’ aspects of another individual’s behaviour (Whiten et al., 2004). One distinct form of social learning is imitation, which is differentiated from other forms of social learning mechanisms because the social learner copies the precise details and sequences of behavioural actions employed by the model (Heyes, 1993; Byrne, 2003; Tomasello et al., 1993). Thorndike (1898) originally identified imitation as engaging in an act after watching the act performed by a model (Thorndike, 1898). This study adopts a rather ‘broader’ definition of imitation proposed by Whiten and colleagues (2009b) who extend the ‘restricted’ concept of imitation, which only defines the copying of purely ‘bodily’ actions, to a more inclusive criteria where the “copying the form of an action” also involves tool-related movements (Whiten et al., 2009b, p. 2418). Some examples of imitation therefore comprise the copying of facial expressions (Meltzoff and Moore, 1977), vocal imitation such as involved in bird song acquisition (Heyes, 1994) as well as tool-manipulations such as poking and lifting (Custance et al., 1999; Whiten et al., 2005; Dean et al., 2012).

A simple operational definition of imitation (see e.g., Whiten et al., 2004 and Whiten et al., 2009b) states that imitation is the copying of demonstrated behaviour(s) from a model that may lead to a desired outcome such as, for example, the production of cultural artefacts (Table 5.1). Emulation refers to observational learning from a model by considering only the end-state product or result, also referred to as ‘end-state copying' in a sense that emulation "is classed within copying, but it is only the end-state(s) of what the model has done that is copied" (Whiten et al., 2009b, p. 2419). Crucially, emulation is argued to be purely result-oriented form of learning. Therefore, the behavioural actions or techniques employed by the model are not necessarily copied faithfully. In other words, in end-state emulation the actions applied to achieve the result are learned individually (Tomasello et al., 1987; Nagell et al., 1993). Thus, emulation here is defined as the copying of a result (i.e., 'end-state') without copying the behaviours that have led to that result (Table 5.1).

There are other forms of social learning that do not include the direct 'copying' of behavioural aspects. One of such social learning mechanism has been identified as 'stimulus enhancement' (Table 5.1). Stimulus enhancement takes place when an individual's attention is drawn to an object which is handled by another individual and the behavioural patterns exhibited towards the object are then achieved by individual learning (Matthews et al., 2010). Similarly to stimulus enhancement, attention can be drawn to a specific location, a mechanism termed 'local enhancement'. Other forms of social learning that are not classed under copying or enhancement have been identified, such as 'observational conditioning', eliciting an aversive reaction towards a stimulus (such as fear) after observing others having an aversive reaction towards the same stimulus, or 'affordance learning' where properties or functions of an object are learned; neither of these involve an active 'copying' process of actions or goals, however (Whiten et al., 2004).

Table 5.1: Descriptions of social learning mechanisms adopted from Whiten et al., 2004 and 2009b.

Imitation	Copying of demonstrated behaviour(s) exhibited by a model (e.g., the actions involved in the production of an artefact)
End-state emulation	Copying of a result without copying the behaviours that have led to that result
Stimulus enhancement	Attraction of attention to an object in the environment due to the behaviour of another individual which is subsequently repeated by trial-and-error learning in the observer
Local enhancement	Attention is drawn to a specific location in the environment causing the observer to use that locality more frequently
Observational conditioning	Learning a response (aversive or positive) to a stimulus by observing other's reactions to the same stimulus

Importantly, in the search for the social processes that can explain how lineages of cultural traditions emerge, the main focus has been to clarify the social learning mechanisms required for the high-fidelity transmission of cultural information, due to the crucial role fidelity plays in the 'cultural inheritance', or long-term maintenance, of detectable patterns of cultural variation (Galef, 1992; Heyes, 1993, 2009; Shea, 2009; Lewis and Laland, 2012; Mesoudi et al., 2013). In fact, Shea (2009) specifically argues that high-fidelity copying mechanisms affect variation generated by unintentional copying errors in specific ways. While the production of unintentional copying error is an important variation-generating process, the perpetuation of cultural features depends on the prevention of the loss of such modifications that enter the course of cultural transmission through faithful high fidelity copying mechanisms. In other words, high-fidelity copying mechanisms counter-act, or reduce cultural mutation rates, which threaten to erase, or 'erode' the emergence of distinct archaeological modifications in the repetitive course of cultural transmission (Chapter 3).

Therefore, social learning mechanisms with the capacity for high copying fidelity provide the key advantage for the preservation, spread and perpetuation of cultural trends over long-term cultural transmission. In the debate surrounding which social learning mechanism contains such capacity of high-copying fidelity, a dichotomy between two predominant social learning mechanisms arose in the past literature. The social learning mechanism usually distinctively associated with the faithful transmission of cultural variants is imitation (Boyd and Richerson, 1985; Byrne and Russon, 1998; Laland, 2004). There seems to be an overall agreement that imitation has the capacities for faithful propagation of detailed morphological modifications via 'high fidelity copying' because of the more 'complete' and 'accurate' acquisition of both actions and the end-state product of an artefact. Thus, imitation in theory has important implications for the emergence and long-term propagation of distinct artefactual traditions (Mithen, 1999; Mesoudi et al., 2013). In that respect, the link between imitation and high-copying fidelity has been expressed by Heyes (2009), Tennie et al. (2009), Whiten et al. (2004, 2009b) and more recently Lewis and Laland (2012) and Mesoudi et al. (2013). Importantly, imitation is argued to sufficiently reduce cultural mutation rates necessary to sustain the long-term propagation of modifications in the course of cultural transmission (Shea, 2009). It is for these reasons that scientists argue that imitation may also mediate the gradual and incremental nature of human cumulative cultural evolution, a notion also referred to as 'ratcheting' (Boyd and Richerson, 1985; Tomasello et al., 1993; Tomasello, 1999; Shea, 2009; Tennie et al., 2009, Dean et al., 2012; Kempe et al., 2014). In other words, imitation has the capacity for change via descent ('descent with modification') because high copying fidelity allows for the long-term perpetuation of cultural traditions (descent) where novel modifications can be additionally incorporated. Therefore, a capacity for descent via high copying fidelity is a fundamental principle of ratcheting.

The polarization between the two learning mechanisms, imitation and emulation, has been derived from the theory that, unlike imitation, emulation does not have the same capacity to sufficiently sustain cultural variants in the long-term (Galef, 1992; Tomasello, 1993; Tomasello, 2009, p. 520-521). Since emulation comprises the end-state copying of an object or behaviour but not the action sequences or 'behavioural means' to achieve the goal, emulation is argued not to contain the sufficient capacity to maintain cultural traditions over the course of cultural transmission to the same extent (Tomasello, 1999). Therefore, emulation could be understood as a 'low-fidelity copying mechanism' based on the theory that end-state copying, or result copying, alone is limited in its capacity for the long-term preservation of traditions (Tomasello, 1999, 2009) [1]. However, the assumption which of these two social learning mechanisms emulation or imitation are sufficient for the social transmission of repeated patterns of behaviours that could specify as ‘behavioural traditions’, such as manual manufacturing traditions, has never been tested empirically in respect to the evolution of artefactual culture. Indeed, the issue of whether copying error rates are significantly different in the two modes of learning has not been tested.

Doubt regarding the differential impact of contrasting social learning mechanisms on the long-term transmission of morphological artefactual modifications has been established by Caldwell and Millen’s (2009) human-based cultural chain transmission experiment. Participants were asked to each manufacture a paper aeroplane with the aim to make them fly the greatest possible distance. Participants were either exposed to the context of imitation (observation of the building of aeroplanes), emulation (only viewing the completed planes and flight distances), or a teaching (being verbally advised about the building of a plane whereby flight distances could also be inquired). The findings suggested that participants were equally good at incrementally improving the flight distance of the previous generation’s paper aeroplanes, irrespective as to whether they were placed in a teaching, imitation or emulation context. Low-fidelity copying mechanisms, such as emulation, facilitated the cultural transmission and incorporation of novel adaptive modifications equally compared to high-fidelity copying mechanisms commonly associated with imitation and teaching (Caldwell and Millen, 2009). A recent experiment by Wasielewski (2014) expanded on Caldwell and Millen’s (2009) findings by demonstrating that for less ‘transparent’ (i.e., ‘opaque’)

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[1] In respect to the animal kingdom, there is ongoing dispute regarding the presence of imitation in non-human animal species, with chimpanzees often referred to as ‘emulators’ (e.g., Tomasello, 1993). Theoretical statements in regards to animal culture has been heavily contested in the face of current interdisciplinary evidence. Overarching evidence to date suggests that a wide range of animal species, including our closest living relative the chimpanzees, are capable of imitation amongst other social transmission processes associated with the spread and maintenance of cultural traditions (Russon and Galdikas, 1993; Custance et al., 1995; Atkins and Zentall, 1996; Russon and Galdikas, 1993; Byrne and Russon, 1998; Zentall, 2003; Whiten et al., 2004; Horner and Whiten, 2005; Buttelmann et al., 2007; Hopper et al., 2007; Huber et al., 2009; Matthews et al., 2010; Slagsvold and Wiebe, 2011; Galef, 2012; van de Waal and Whiten, 2012; Zentall, 2012; Hobaiter et al., 2014; Kis et al., 2014; van Leeuwen et al., 2014). In addition, there is now experimental, ethnographic and phylogenetic evidence that strongly supports the theory that chimpanzees and other nonhuman animal species display between-population behavioural variation that cannot be explained by genetic and ecological factors (Fisher and Hinde, 1949; Boesch and Boesch, 1990; Whiten et al., 1999, 2005; Horner et al., 2006; Lycett et al., 2007; deWaal, 2013; Hobaiter et al., 2014). However, humans only may have evolved specific social-cognitive mechanisms for ‘complex’ culture exhibited in the form of multiple instances of traditions reliant on the extensive and cumulative ‘ratcheting (Herrmann et al., 2007; Dean et al., 2012).

tasks, such as those tasks were information from the end-state product are not enough to reconstruct the product at high fidelity, imitation may be essential for the sustainability of cultural traditions. Wasielewski (2014) suggests that a more ‘opaque’ cultural artefact in the real world could be core-shaped artefacts like Acheulean; in fact, others appear to share the notion the artefact production of Acheulean handaxes is sufficiently complex to be associated with the requirement for imitation (e.g., Mithen, 1999; Shipton, 2010). Wasielewski (2014) argues that spaghetti towers and paper aeroplanes might be sufficiently transparent such that enough information can be acquired from the end-state product to generate copies at high copying fidelity. In Wasielewski’s (2014) experiment, participants were grouped into microsocieties and provided with the task to generate weight bearing devices using clay and reed and a wooden stand. Participants were either exposed to a learning condition involving the ability to imitate actions that led to the end-state product (without viewing the end-state product), to emulate only the end-state product (relevant action behaviours were not shown) or they were not provided with any social information regarding the end-state products, thus, they did not see the devices from other members of their society. In one additional condition, participants viewed both the actions and end-state products. Social learning was enabled by means of a replacement method where the ‘oldest’ member of the microsociety was replaced with a new member in 5min intervals. This gave participants the opportunity to view the devices or the actions employed to build the devices by other members in their microsociety before constructing their own weight bearing devices. The experiment by Wasielewski (2014) demonstrated a clear trend that the best scores were achieved only in the social conditions that allowed learning from the behaviours applied to building the devices (i.e., imitation). Thus, the study appears to extend the notion of current research literature that imitation may be required for artefact traditions that comprise a more complex, or ‘opaque’, manufacturing process that is not easily “reverse-engineered” (Wasielewski, 2014, p. 169).

Crucially, the study of individual-level social learning mechanisms is deemed important in respect to the factors necessary in the emergence and spread of cultural traditions. Yet, little direct attention has been paid to how different social learning mechanisms impact variability in traits of artefacts as might be seen in the archaeological record. In this respect, this study aimed to elucidate whether emulation or imitation exhibit significantly different levels of copying fidelity, such that they might bear on debates concerning lasting shape traditions. This experiment particularly emphasized the effects of the social processes on the ‘shape’ of the artefacts. Shape in the archaeological record may have specific functional and/or aesthetic relevance which is one potential reason explaining its long-term preservation in lineages of artefactual culture, such as ‘handaxes’. Some of the first prehistoric cultural artefacts known to contain high shape preservation across spatial and temporal terms is the Acheulean (Roche, 2005; Gowlett, 2006). The high shape preservation in the reductive stone tool technology of the Acheulean is particularly interesting because reductive manufacturing processes were suggested (Chapter 3) to produce higher cultural mutation rates by means of copying errors compared to readily reversible manufacturing traditions; thus, making stone tool traditions more prone to shape degradation (Chapter 3). In this respect, the study of the effects of different social learning mechanisms on shape preservation may offer answers as to how the decrease in cultural shape mutation rates is possible in particular regards to reductive manufacturing traditions. Findings of this study could further provide crucial implications regarding the specific mechanisms required for the emergence and spread of lasting artefactual shape traditions.

The purpose of this study was to understand whether contrasting social learning mechanisms generate diverging patterns of shape copying error within an experimental context where rates of variation can be compared in a controlled laboratory environment. In this experiment, two experimental conditions were employed, utilising a simple copying task where participants were asked to faithfully copy a foam handaxe target form using a standardised block of floral foam and a plastic table knife. The experimental conditions varied in respect to the learning conditions provided. In an ‘imitation condition’, participants were shown the end product of the target form as well as a video demonstration that displayed different successful techniques employed in the manufacture of the target form. In the ‘emulation condition’, participants were only exposed to the end state of the target handaxe form. It was predicted that imitation, which is associated with high-fidelity copying, generates lower rates of shape copying error at a statistically significant level compared to emulation. Alternatively, it was proposed that end-state emulation, a social learning mechanism associated with low copying fidelity, generate higher rates of shape copying error.

An additional analysis was generated to ensure that differences in the rates of shape copying errors could be confidently attributed to the differences in the learning context. Therefore, this analysis served to reject other possible hypotheses that could give explanations for significant differences in the shape error rates between the two experimental conditions. This second analysis therefore specifically tested for imitation by investigating whether participants in the imitation condition matched the behavioural sequences to those manufacturing techniques demonstrated more so than participants in the emulation condition.

5.2 Methods and materials

5.2.1 Participants

A total of 60 participants took part in this experiment. The majority of these participants were undergraduates from the University of Kent who were recruited through the university's Job Shop. The experiments were undertaken in a laboratory facility at the School of Anthropology and Conservation, University of Kent. In terms of experimental participants, 30 were female (mean age = 23, SD = 5.2, age range = 18-44 years) and 30 were male (mean age = 24, SD = 4.8, age range = 18-34 years). All participants were reimbursed with £4 for their participation. The data for one of the experimental conditions (the 'emulation condition') stemmed from the participants recruited for the 20min time condition in Chapter 4. This was because the emulation condition contained the equivalent experimental set-up as the 20 minute time condition. Rather than recruiting a new set of 30 participants to repeat the 'same' experimental task, it was deemed more efficient to re-use the appropriate data for this experiment.

5.2.2 Materials

Standardised blocks supplied by OASIS DRY SEC foam, a type of dense, porous and hard floral foam were used to make the handaxe replicas. These blocks are machine-cut in a pre-determined, standardised format and, therefore, allowed for maximum replicability of starting conditions. The blocks measured 22.3cm in length, 11cm width and 7.8cm in thickness. The experimental 'handaxe replicas' were produced from this foam using a simple plastic table knife. The plastic knife was suitable for use in either the left or right hand. Details regarding both the dry plant foam and the plastic knife can be found in Chapter 2; the dimensions of the target foam model are displayed in Chapter

4 (Figure 4.2). In this experiment, an ASUS notebook (K52Jc series) was used to show a video demonstration on a wide screen measuring 34.5cm x 19.3cm. Participants were also provided with the option to use mouth protection and eye protection glasses to protect against irritations resulting from small parts of dispersing foam dust. All participants also wore a lab coat to protect their clothing from the foam dust. A time tracking device (employed as a countdown timer) was also provided to the participants; however, it should be noted that participants were also verbally reminded of the remaining time left for the copying task at regular time intervals. Video recordings were undertaken using a DSLR Fujifilm Finepix HS 20 (focal range of 24 - 720mm) and a tripod.

5.2.3 Experimental conditions

The experiment was divided into two alternative conditions.

5.2.3.1 Condition 1 – The imitation condition

The first condition tested the effects of imitative learning on the production of shape copying error. In this experimental condition, termed the ‘imitation condition’, participants were shown the relevant manufacturing techniques involved in the production of the target form and were also shown the end product of the target form (Table 5.2). These action sequences were displayed in the form of a video demonstration that was four minutes and 50 sec long. A shortened demonstration of the manufacturing process (as opposed to the complete process) was sufficient to clearly demonstrate the main six distinctive manufacturing techniques involved in the production of the target form. Yet, the video demonstration was not overtly long, and prolonged exposure to repetitions of the same behaviours were avoided, such that potential effects from excessive exposure to the manufacturing actions, like memory loss and a decrease in attention, could be minimised. It should be noted that the video demonstration was produced and edited in a fashion where the prolonged exposure to the final target form was avoided. Thus, participants in the imitation condition were not exposed to the final target form any longer than the participants in the alternate condition. The choice of a video demonstration was the preferred method over the alternative option of a human demonstrator because the video format allowed for the ‘total repeatability’ of the demonstrated behaviours across all participants. In addition, since a demonstration of the manufacturing techniques is present in the imitation but not the emulation context, the choice of the video rather than a demonstrator automatically controlled for methodological inconsistencies arising through a form of social influence termed ‘social facilitation’. Social facilitation here is defined as the improved performance in a task simply due to the presence of another member who is involved in the same task (Zajonc, 1965; Dindo et al., 2009); in the case of the imitation context this member would be the demonstrator. Experimental research has provided evidence that social facilitation improved performance compared to the context where individuals perform a task alone (e.g., Zajonc, 1965; Galloway et al., 2005; Dindo et al., 2009). In this respect, by using a video demonstration possible confounding effects elicited by social facilitation through the presence of the demonstrator were controlled for. This allowed for any differences in the results between the experimental conditions to be reliably associated with the intended controlled manipulations of the social learning context.

5.2.3.2 Condition 2 – The emulation condition

The second condition assessed the effects of end-state copying (emulative learning) on the production of shape-copying errors in the copying task. A video demonstration was not provided in this condition. Participants were only given the opportunity to view the end product of the target replica prior the copying task. This condition was referred to as the ‘emulation’ condition.

5.2.4 Experimental design and procedure

All 60 participants were divided into the two experimental conditions so that there was an equal number of participants (n = 30) in each condition. Within each condition, participants were equally divided into 15 females and 15 males to control for sex differences, as explained in Chapter 3. In addition, both sample groups consisted each of 27 right-handed individuals (90% of the group) and three left-handed participants (10% of the group). This distribution of left-and right-handed individuals is representative to that of the natural population distribution of modern human populations (Toth, 1985a; Corballis, 1989; Raymond et al., 1996). Inconsistencies in handedness were unlikely to be of relevance given the overall experimental design and also because numbers were balanced across conditions.

In the experimental task, all participants were assigned to an experimental condition alternatively and took part only once in one of the two conditions. In both conditions, participants were asked to copy the shape of the foam target handaxe form as accurately as possible. The same model target form was previously utilised in the experiment investigating the effects of various time constraints, therefore, details regarding the shape dimensions of the target form can be found in Chapter 4. All participants were advised to pay attention to the overall form and shape features of the target form but to prioritise the copying of the handaxe *shape*. The instructions also clarified that video recording would take place during the copying task for further analysis. To encourage their motivation to perform well, all participants were informed that the person who produced the most accurate handaxe copy (the replica with the lowest shape copying error), would win a prize in the form of a £20 book voucher from a well-known internet book seller in addition to their £4 reimbursement.

All participants read the task instructions before beginning the experimental task. In the imitation condition, participants were shown a four and a half minute long video demonstration illustrating the action sequences employed in the production of the target form (participants in the emulation condition proceeded immediately with the next step in the experimental procedure). In both conditions, participants were provided with one minute to inspect and handle the target handaxe form from all sides and were verbally reminded of the instructions. When the minute was over, they were placed at a table and provided with one standardised foam block and a plastic knife for the manufacturing task. They were given a time frame of 20 minutes to complete the copying task. To control for memory effects, the target handaxe remained with the participants throughout the experiment. The participants were also advised that they may compare the target handaxe form with their own foam replica from any side or angle at any point desired during the experimental task. All participants were provided with a time tracking device which allowed them to track the remaining time of the experiment whenever desired. In addition, at five minute intervals the participants were reminded of the remaining time left until task completion. There was only one attempt at the experimental task but all participants managed to complete the task within the time limit given.

Participants were also allowed to wear spectacles and contact lenses if so required for close-up tasks to avoid major inconsistency in visual perception. The use of external aids to improve perceptual accuracy (e.g., scaled rules) was not permitted.

5.2.5 Introducing the video analysis

An analysis of the video recordings of participants' behaviour was conducted to test whether participants in the imitation condition matched the behaviours seen in the video demonstration to higher degree compared to participants in the emulation context. Thus, the aim of the video analysis was to collect direct evidence for imitation. On the basis of the video analysis, therefore, it could be more confidently assured that any statistical differences in the rates of shape copying error between the imitation and emulation conditions could be accurately attributed to the differences in the learning context provided. Therefore, it is emphasized that the goals of this video analysis were rather discrete, in terms of being specific to the overall aims of the main analysis.

The video analysis was preceded by one round of initial observations of all videos in order to collect a 'catalogue' of behaviours represented. For the analysis, two overall groups of behaviours were recorded. The first group of behaviours recorded were termed 'matched behaviours'. Matched behaviours were identified as the behaviours displayed in the demonstration video. All demonstrated behaviours were clearly defined prior analysis on the basis of the video demonstration, generating a matrix of distinct behavioural categories. All those behaviours that were not displayed in the demonstration were placed into the second group of behaviours referred to as 'aberrant behaviours'. Thus, aberrant behaviours were defined as those behaviours that were not demonstrated in the video. Aberrant behaviours were identified defined prior data analysis via observation of the videos.

To begin with, the videos were analysed for the presence of 'matched' versus 'aberrant' behaviours. For every video, any observed behaviours were recorded on a recording sheet. A new recording sheet was used for every video. The recording sheet consisted of two separate behavioural matrices; one matrix comprised the entire set of matched behaviours and the other matrix comprised the entire list of aberrant behaviours. On the recording sheet, all behaviours were identified by separate behavioural categories and short verbal definitions (Table 5.2). Thus, during the viewing of each video, the main instructor could scroll along these behavioural matrices and then tick off those matched and aberrant behaviours that were observed in the video. Behaviours not observed in the video would be left blank on the recording sheet. Table 5.2 illustrates an example of the matrix defining the matched behaviours as described on the recording sheet. Table 5.2 also illustrates the behavioural recordings of matched behaviours from two video samples from the imitation condition.

Table 5.2: The recording sheet for 'matched' behavioural categories. The tick demonstrates were behaviours were present in the two video samples from the imitation condition.

Sample recording sheet	**Matched behaviours**	Imitation video 1	Imitation video 2
1.1	Minimum six consecutive corners	✓	
1.2	Other: minimum of three non-consecutive corners		
2.1	Minimum six consecutive margins		
2.2	Other: minimum of three non-consecutive margins	✓	✓
3	Initial tip and base cutting		
4	30 sec scraping to remove foam		✓
5	Two repetitions of scraping and tip and base cutting		✓
6	Final shaping via scraping		✓

Following the behavioural recordings, each video was then assessed for the level of copying fidelity at which stage a 'fidelity code' was assigned; a procedure for this will be explained in detail below. Generally speaking, the fidelity codes followed a simple principle by which a higher level of matching to the demonstrated behaviour resulted in the assignment of a 'higher' fidelity code. In other words, the more of the demonstrated behaviours were copied, the higher the number of the fidelity code. The fidelity codes were then statistically compared between the two experimental conditions. The purpose of the analysis was to test whether the imitation condition exhibited 'higher' fidelity codes compared to the emulation condition at a statistically significant level. Thus, on the basis of the fidelity codes, the statistical analysis established whether there was a significant difference in the level of matching to the demonstrated behaviours between the two conditions. The video analysis was also assessed for intra-rater reliability.

5.2.5.1. Definitions of 'matched behaviours'

This section gives an account of all six behaviours demonstrated in the video that, if copied, would then be recorded as 'matched behaviours'. All matched behaviours were clearly defined preceding the video analysis. A summary of the behavioural categories displayed in the video demonstration can be viewed in Table 5.3.

Table 5.3: A summary of the sequence of six demonstrated manufacturing techniques which were divided into eight behavioural categories.

Categories	Knife	Foam
1.1	Cutting	'Corner cutting': minimum six consecutive corners
1.2	Cutting	'Corner cutting': minimum of three non-consecutive corners
2.1	Cutting	'Margin cutting' minimum six consecutive margins
2.2	Cutting	'Margin cutting': minimum of three non-consecutive margins
3	Cutting	Initial tip and base cutting
4	Scraping	30 sec scraping (dominant foam removal technique)
5	Both	Two repetitions of scraping and tip and base cutting
6	Scraping	Shaping of feature on one of the handaxe faces

The six techniques defined in the behavioural criteria in Table 5.3 were carefully chosen because these behaviours represented the main procedural steps undertaken to produce the target handaxe form. In addition, they comprised a set of clearly distinct yet simple manufacturing techniques that could be shown to participants within a short four-minute video demonstration. Therefore, this multi-action sequence of manufacturing behaviours could be understood as a simple 'set of instructions' involved in the manufacture of the target form without tracing for memory effects.

The following section describes the definitions for the individual behavioural categories for the demonstrated behaviours.

5.2.5.1.1 Cutting corners (categories 1.1 and 1.2 in Table 5.3)

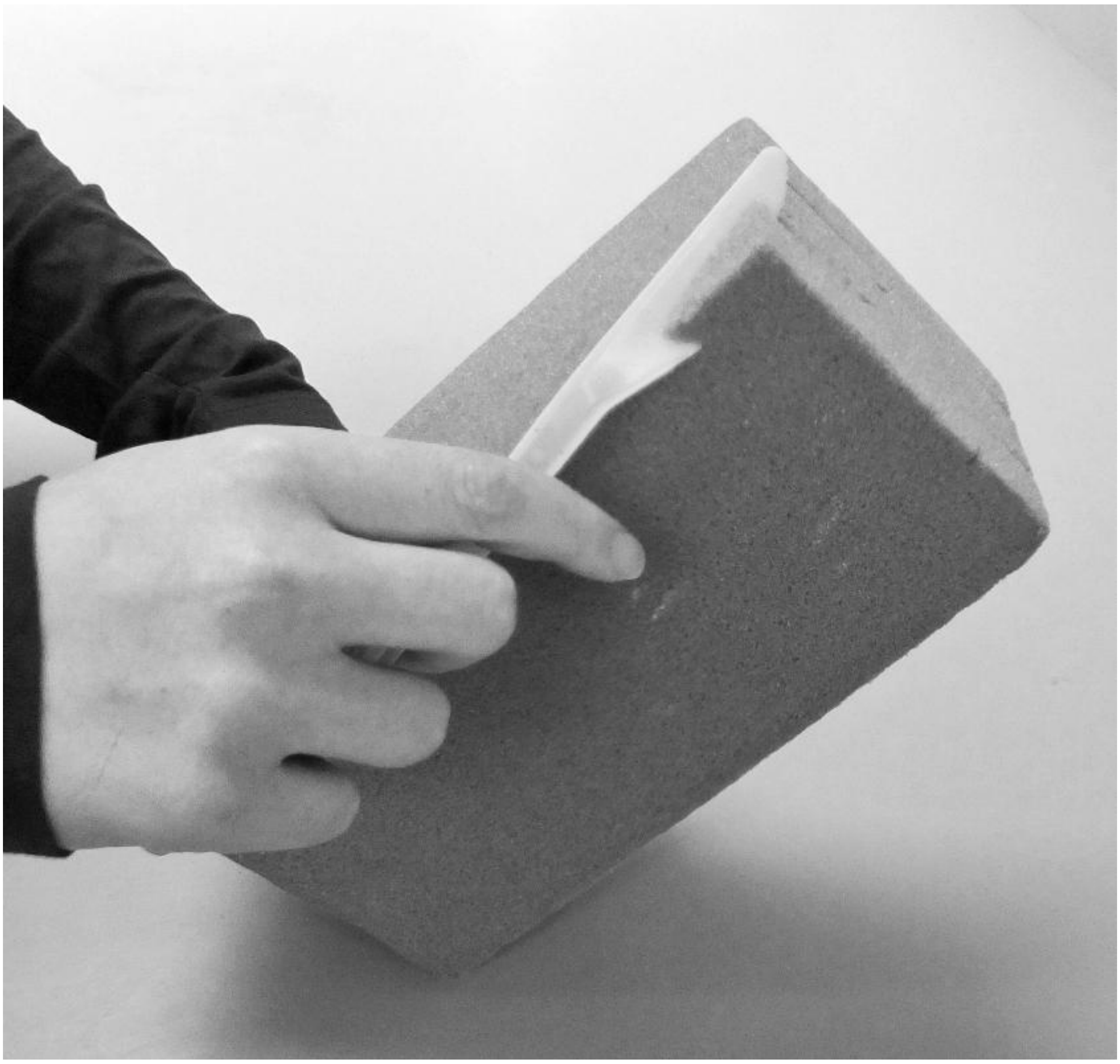

Figure 5.1: Example of cutting corners from a standardised foam block.

The behavioural category for ‘corner cutting’ was counted if one corner was cut at a time as depicted in Figure 5.1. Cutting here is defined as a relatively slow and controlled motion, which is executed requiring little to medium force. Since the video demonstration displayed the cutting of corners on *unmodified* foam, any cutting of the corners was not recorded as a matched behaviour if a cross-section of foam was previously removed at that location. In addition, corner cutting was not counted if a margin was removed prior to corner removal or if two corners were removed in the format of one cross-section along the margins.

1.1 Cutting a minimum of six consecutive corners

In this behavioural category defining, ‘corner cutting’, it required participants to cut at least six consecutive corners, as defined by categories 1.1 in Table 5.3.

1.2 Cutting a minimum of three non-consecutive corners

This category was scored when the participant cut at least three non-consecutive corners. Any corner cutting beneath the count of three was discarded. Naturally, participants could only score in one of the two categories defining corner cutting. The purpose of this behavioural category was to show that participants still copied the demonstrated behaviour despite failing the exact count as displayed in the video.

However, it might also be worth noting that the categories for corner cutting were evaluated differently when assessed for the level of copying fidelity in the next analytical stage. Thus, a ‘perfect match’ to the demonstrated behaviours in the video was evaluated as displaying higher copying fidelity when six consecutive corners were cut (category 1.1 in Table 5.3). The category displaying the lower count of three non-consecutive corners (category 1.2 in Table 5.3) was evaluated as scaling lower in the fidelity coding system and was associated with ‘imperfect copying’.

5.2.5.1.2 Cutting the margins (categories 2.1 and 2.2 in Table 5.3)

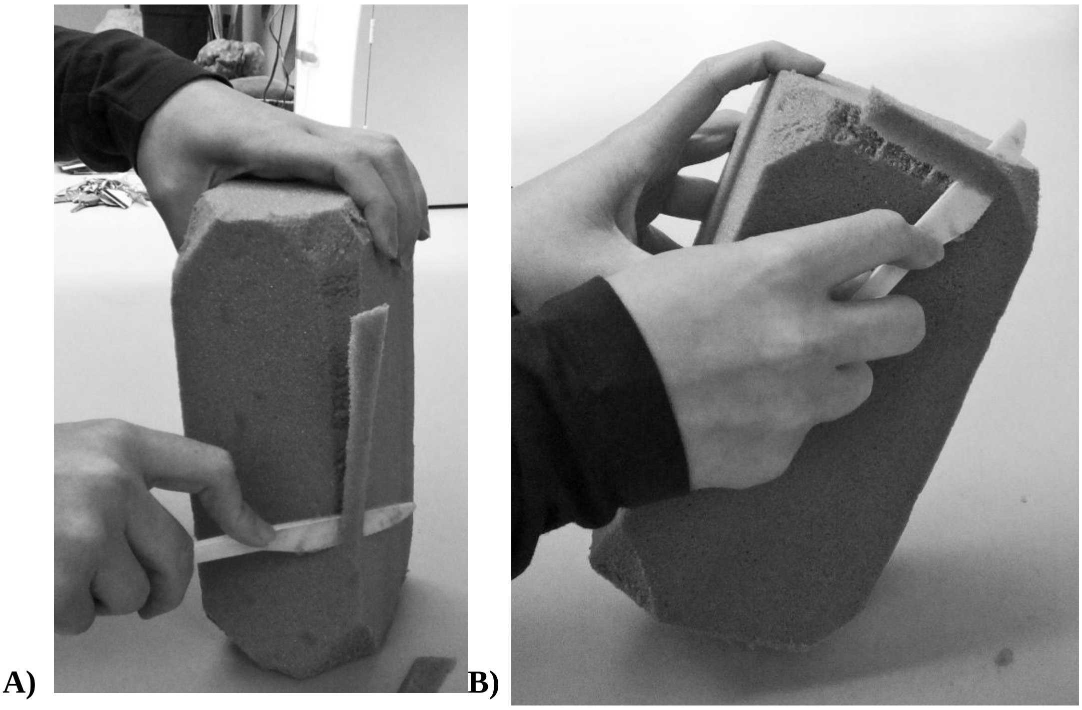

Figure 5.2: Example of cutting long margins (A) and small margins of the foam block (B).

Participants scored successfully in the behavioural category defining ‘margin cutting’ if a determined effort was made to cut the long and/or the small margins (both displayed in Figure 5.2). Similar to the video, the cutting of margins was only recorded if it took place on *unmodified* foam. The only exception considered was the previous removal of the corners, due to the natural procedure that margin removal came next in the sequence. However, if it became obvious that the participants attempted to remove cross-sections across the face of the foam block, where both corners and margins could be removed as part of this process, these combined instances of corner and margin removal were not recorded. This is because participants would fail to show the specific procedural sequence which this behavioural category describes, as represented in the video.

2.1 Cutting a minimum six consecutive margins

Similar to the example of corner cutting, this category applied to participants who cut at least six consecutive margins.

2.2 Cutting a minimum of three non-consecutive margins

Participants were recorded in this category if at least three non-consecutive margins were removed by cutting. Again, every participant could only score in one of the two categories defining 'margin cutting'. As with the corner removal, a 'perfect match' to the margin cutting as displayed in the video (subcategory 2.1) was evaluated as displaying higher copying fidelity compared to the 'imperfect' copying of margin removal (subcategory 2.2).

5.2.5.1.3 Initial tip and base cutting (category 3 in Table 5.3)

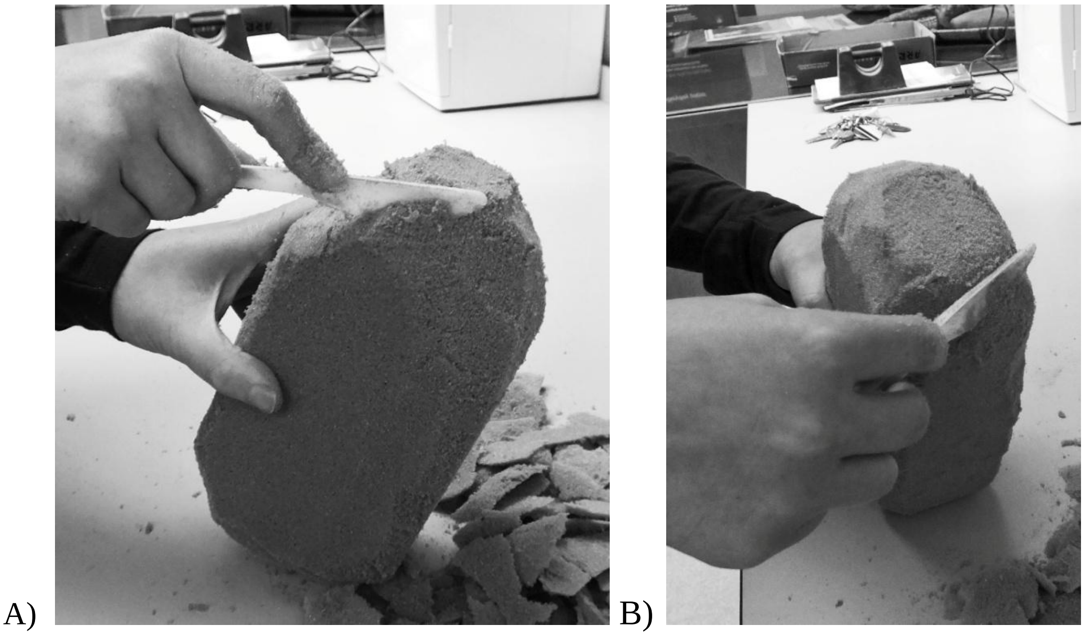

Figure 5.3: Example of cutting foam ends into A) tip and B) base foundations.

The next phase in the demonstration described a relatively short consecutive sequence of tip and base cutting so that the entire foam block obtained a more oval shape (Figure 5.3). If only one of the ends was shaped by cutting movements but not the other, the behaviour was marked as an aberrant behaviour, as the video clearly demonstrated an alternative pattern.

5.2.5.1.4 Scraping as the dominant foam removal technique (category 4 in Table 5.3)

Figure 5.4: Example of scraping movements as the main technique of foam removal.

Scraping was the main technique employed for foam-removal. It was applied consecutively in elongated sequences and all around the foam block. Scraping movements could be distinguished from other techniques because the blade faced the foam block while it was moved over the foam (Figure 5.4). During scraping, the blade could even slightly face in the direction opposite to motion. Scraping could also be clearly distinguished because it was a smooth movement whereby foam debris separated from the block in a pulverised form. There were specific reasons why a time measure was employed to investigate scraping as a matched behaviour. Since scraping was a rapid and highly repetitive movement, the use of measures of frequencies, which are traditionally applied to investigate and record behavioural occurrences (e.g., Martin and Bateson, 1993), were unsuitable in this context for establishing whether scraping movements of participants were matched behaviours. This is because, unlike the long bout of scraping behaviours in the video demonstration, scraping could be exercised in multiple short bursts, and in exchange with other removal techniques like cutting motions, where high frequencies of the scraping behaviours were still achievable. Still, multiple short bursts of scraping were not representative of how the video demonstrated scraping motions. Since the video demonstration displayed scraping in one prolonged and consistent sequence of 30 seconds, this time limit was taken as a minimum threshold that participants had to reach if scraping was to be successfully counted as a matched behaviour. Long bouts of a foam removal employed by a specific technique were generally indicative that the behaviour was adopted as the main focal technique of foam removal. Thus, the 30 seconds time limit for *consistent* scraping could be conceptualised as a ‘proxy’ that scraping was the dominant foam removal technique.

If scraping was applied in one direction it was treated equally as a matching the behavioural category indiscriminately as to whether the motion was headed forth or back. However, if scraping was applied in a forth and back motion simultaneously, this instance was treated as an aberrant behaviour. Other scraping instances were categorised as aberrant where parts of the knife other than its blade were used.

5.2.5.1.5 Two repetitions of scraping and tip and base cutting (category 5 in Table 5.3)

The next phase in the video demonstration described repetitions between bouts of scraping and shaping the handaxe’s base and/or tip by cutting. This means that between bouts of scraping, the demonstrator engaged in cutting the tip and/or the base. At least two repetitions had to be displayed for this behaviour to be recorded as a matched behaviour.

5.2.5.1.6 Final shaping via scraping (category 6 in Table 5.3)

Figure 5.5: Final shaping via scraping.

In the last behaviour of the sequence, one face of the handaxe replica was modified into a shape as visualised in Figure 5.5. There had to be a determined effort to shape the entire structure by scraping. The simultaneous mixing of foam removal techniques such as cutting and scraping was treated as an aberrant behaviour. If, on separate occasions, the participants cut the feature but returned at a later stage to scrape the entire structure (at which point the original shaping may have disappeared as a result of overall foam removal), the first instance of shaping by cutting was recorded as an aberrant behaviour and the second instance of shaping by scraping was counted as a matched behaviour for this category.

5.2.5.2 Definitions of ‘aberrant behaviours’

This section displays a brief overview of ‘aberrant behaviours’, describing all manufacturing behaviours observed that were not illustrated in the video demonstration. The most common categories for aberrant behaviours can be viewed in Table 5.4. Initial examination of the videos provided the ‘behavioural matrix’ comprising the complete set of aberrant behaviours, as illustrated in Table 5.4. Provided that the main purpose of the video analysis was to test for the presence of imitative learning, the list of aberrant behaviours was not investigated to the same extent by the fidelity coding system as the list of matched behaviours. However, since the presence of aberrant behaviours could be understood as a deviation from copying fidelity, the investigation of aberrant behaviours at least on a general presence/absence basis still merited consideration as it provided further insight into the actual level of copying fidelity.

Table 5.4: Definition and visual presentations of common behaviours described as ‘aberrant behaviours’.

	**Scraping with the tip/end of the knife** In this case, either the knife’s tip or end but not the blade were used to scrape or shape foam structures.
	**Cutting towards the thumb** Rather than placing the knife blade away from the hand, the blade was inverted so it faced the thumb. The knife was pushed towards the thumb in a motion reminiscent of fruit peeling.
	**Scraping with the knife back** In this scraping alternative, the blade did not face the foam block as displayed in the video demonstration but was oriented upwards while the back of the blade was used for scraping.
	**Holding knife like a pen** The knife was not held in the palm of the hand but between thumb and index finger.
	**Chopping/slicing** The blade was sliced on the surface of the block. This slicing motion could be smooth and fast but could also be applied with force (almost in a chopping motion), often resulting in the blade breaking or becoming stuck. The blade faced in the direction of motion, which made it easily distinguishable from scraping (in scraping, the knife faces the foam block or opposite motion).
	**Removing cross-sections of large blocks of foam** Foam block removal was identified by the removal of larger pieces of foam blocks. Large blocks of foam required an extensive amount of cutting and re-appliance of the knife to remove these large pieces.

5.2.5.3 Video analysis: assignment of ‘fidelity codes’

Every video was systematically tested for the degree to which each participant’s manufacturing behaviours matched the video demonstrations, therefore evaluating the level of copying fidelity. Copying fidelity was assessed by assigning one ‘fidelity code’ to every video. The fidelity code ranged from the lowest degree of copying fidelity starting at code zero up to the highest degree of copying fidelity at code seven (Table 5.5). In the first instance, the fidelity code reflected the numbers of demonstrated behaviours that were copied. Thus, the higher the number of ‘matched behaviours’, the higher the fidelity code assigned.

However, the final assignment of the fidelity code depended on the combination of two additional factors. Each video was also assessed as to whether it followed the exact sequence of manufacturing behaviours as illustrated in the video demonstration (chronology as displayed in Table 5.3). If the sequence was also matching with that of the video, it would be given a ‘complete sequence’ status. If a video’s sequence of manufacturing techniques was not matching with that of the video demonstration, it would be given a ‘mixed sequence’ status. It may be noted that some behaviours displayed in the video may naturally occur before others during production, which means that the manufacturing process may pose some constraints on the independency of individual behaviours to appear in any possible order. However, it may be stressed that *all* demonstrated behaviours could vary in their chronological occurrence to some degree, which makes a simple test of sequence adherence purposeful. In this experiment, therefore, behavioural sequence was simply assessed on the basis of whether or not it was ‘perfectly’ matching with the chronology displayed in the video, which was a sufficient assessment of ‘sequence adherence’ for the purpose of the video analysis.

Mixing up the sequence and missing one or more demonstrated behaviours was treated as a deviation from copying fidelity and resulted in a fidelity code one step below the ‘complete sequence’ category (best viewed in the examples relating to fidelity codes six and seven in Table 5.5).

Finally, if aberrant behaviours were also present, this additionally affected the final fidelity code awarded. The presence of aberrant behaviours was regarded as a deviation from copying fidelity plus a sequence violation. In the presence of one or more aberrant behaviours, the final fidelity code awarded was one below the recorded number of matched behaviours in combination with the ‘mixed sequence’ status (this scenario is best observed in the combinations relating to codes five, six and seven, Table 5.5).

In short, the assignment of the one fidelity code to every video could be understood as the *combined result* of these three factors 1) number of demonstrated behaviours 2) sequence adherence and 3) presence of aberrant behaviours. In addition, the coding system (Table 5.5) also ‘clustered’ varying combinations of these three factors within one fidelity code. The ‘OR’ sign is therefore placed to separate one combination from an alternative when both sets of combinations were clustered within the same fidelity code.

Overall, this coding system took into consideration multiple factors of deviations from the video demonstration and incorporating these within one integrated multi-dimensional definition of ‘copying fidelity’. Therefore, the purpose of the analysis was to propose a more sensitive and realistic evaluation of the scale of imitation. The following sections describe a more precise break-down of how exactly three individual factors 1) demonstrated behaviours 2) sequence adherence and 3) aberrant behaviours were utilised to identify copying fidelity.

Table 5.5: A coding system was developed that scaled the level of copying fidelity depending on three factors: 1) the total count of copied behaviours that were accurately identified 2) whether the sequence of demonstrated behaviours was adhered to by separating ‘complete’ from ‘mixed’ behavioural sequences 3) presence of aberrant behaviours.

Fidelity codes	Scale of matching behaviours including sequence and aberrant behaviours
7	6 matching behaviours complete sequence
6	6 matching behaviours mixed sequence
5	6 matching behaviours mixed sequence plus aberrant behaviour(s) OR 5 matching behaviours mixed sequence
4	5 matching behaviour plus aberrant behaviour(s) OR 4 matching behaviours mixed sequence
3	4 matching behaviours mixed sequence plus aberrant behaviour(s) OR 3 matching behaviours mixed sequence
2	3 matching behaviours mixed sequence plus aberrant behaviour(s) OR 2 matching behaviours mixed sequence
1	2 matching behaviours plus mixed sequence plus aberrant behaviour(s) OR 1 matching behaviour mixed sequence
0	1 matching behaviour plus aberrant behaviour(s) OR O matching behaviour (aberrant behaviours only)

5.2.5.2.5.1 Coding of demonstrated behaviours

The coding system has been created in a fashion that the degree of fidelity code is very similar to the numbers of demonstrated behaviours copied. In some ways, the fidelity code predominantly reflected the numbers of copied behaviours. However, the final assignment of the fidelity code depended on the other factors, sequence adherence and presence of aberrant behaviours. It is accurate to say that the coding system was strongly weighted in a fashion that the higher the count of matched behaviours the higher the final fidelity code assigned. Thus, the highest possible fidelity code seven could be reached only if all six demonstrated behaviours were copied. The absence of copying resulted in a fidelity code of zero.

5.2.5.3.2 Coding of the sequence

The coding system also considered whether or not the correct sequence of demonstrated behaviours was copied. Every video was assessed whether it illustrated a ‘complete sequence’ or a ‘mixed sequence’ alternatively. It requires some explanation what precisely defines a complete and mixed sequence. The ‘complete sequence’ category comprised those videos where the matched behaviours were displayed in the correct chronological order as in the video demonstration. The ‘mixed sequence’ category defined those videos where the matched behaviours were displayed in the incorrect order compared to the chronological sequence in the video demonstration. If one or more demonstrated behaviours were not copied, the video would automatically result in a ‘mixed sequence’ status. In other words, only if all six demonstrated behaviours were copied in the correct order was it possible to reach a ‘complete sequence’ status.

Videos with the matched behaviours in mixed sequence were moved to one fidelity code below that of the ‘complete sequence’ alternative (see fidelity codes six and seven in Table 5.5). Therefore, if all six demonstrated behaviours were copied in the complete sequence as shown in the video, this would results in a fidelity code of seven. Thus, fidelity code seven sets the highest standard of what could be defined as the maximum possible degree of copying fidelity. However, if the order has been mixed, the fidelity code six would be awarded.

At this stage of the sequence analysis, the additional categories for corner and margin cutting gained relevance, which was previously defined in Table 5.3. In order to receive the ‘complete sequence score’, participants were expected to score perfectly on removing six consecutive corners and margins as demonstrated in the video (thus, they were required to match behavioural categories 1.1 for corner cutting and 2.1for margin cutting in Table 5.3). Obviously, participants additionally had to copy all other demonstrated behaviours in the correct order to achieve a complete sequence score. Conversely, if this was not achieved and at least one of the ‘incomplete’ behavioural categories was recorded instead (behavioural categories 1.2. for corner cutting and 2.2 for margin cutting), the video was recorded as displaying a mixed sequence of matched behaviours.

5.2.5.3.3 Coding of aberrant behaviours

Aberrant behaviours were assessed on an ‘absence or presence’ basis. Firstly, the presence of aberrant behaviours was evaluated as a sequence violation even if the maximum of six demonstrated behaviours were copied in correct order. Secondly, the presence of one or more aberrant behaviours was also treated as an additional deviation from the video demonstration. Therefore, if aberrant behaviours were present, the video would be assigned a fidelity code one level below the fidelity code which would be assigned if only the 1) total count of matched behaviours and 2) ‘mixed’ sequence were considered. Thus, in the eventual case that all six demonstrated behaviours were copied accurately and in the correct sequence, if one or more aberrant behaviours were also recorded, a fidelity code five would be awarded.

5.3.5.4 Alternate version of the fidelity coding system

The main coding system of this study, which is based on the combined and somewhat complex interplay of three factors of defining fidelity copying in this task (matched behaviours, aberrant behaviours and sequence), was tested against an alternative and simplified version of coding system (with less factor levels). The purpose of this second analysis was to confirm that any statistically significant differences in the level of imitation between the two learning conditions was rooted in the underlying data, as opposed to how the main coding system was generated. Therefore, if two alternate versions of the coding system would present similar outcomes this would strengthen the validity of a coding system analysis for this context. The simpler version of a coding system was based on the number of manufacturing techniques *only* (therefore ignoring the factors ‘aberrant behaviours’ and ‘sequence’). Using a smaller number of code categories and the fact that, the award of a fidelity code was prioritised towards altered principles, assured that there was a certain degree of re-assessment of each video regarding the degree of coding fidelity.

Here, the coding system was based on the simple premise that if participants scored zero and one manufacturing techniques, a score of zero was awarded (i.e., representing a ‘low’ level of copying). If two or three manufacturing techniques were copied, a code of one was reported (i.e., representing a ‘medium’ level of copying) and so forth. Therefore, two of the neighbouring matching possibilities were clustered into one fidelity code category. Similar to the main coding system of this study, the resemblance remained that higher numbers of copied manufacturing techniques would be associated with higher-ranking fidelity code. Table 5.6 demonstrates the simplified coding system. For the simplified coding system, the same criteria and definitions for ‘matched behaviours’ was applied as illustrated in Table 5.3 and according to the definitions. The only change was that for corner cutting the subcategories 1.1 and 1.2 were combined into one category that defined that if participants copied a minimum of 3 corners and more, the behaviour was defined as a matched behaviour. The same rule applied to margin cutting: if participants cut a minimum of 3 margins and more, this was defined as a matched behaviour. This means that the coding system was applied to six matched behaviour categories.

Table 5.6: An alternative and simplified version of a coding system tested each video on the level of copying fidelity based solely on the number of copied behaviours that were accurately identified as matching demonstrated behaviours in the video.

Level of fidelity copying	Copying fidelity code	Manufacturing techniques copied
Perfect	3	6
High	2	5 or 4
Medium	1	3 or 2
Low	0	1 or 0

5.2.5.5 Intra-rater analysis

In order to determine the repeatability of the video coding an intra-rater reliability test was undertaken on the original video coding system. An intra-rater reliability test could be understood as one rater conducting repeated sets of measurements. The preferred method to test intra-rater reliability here was to employ a form of correlation termed ‘intra-class correlation’ which specifically assessed whether the repeated sets of measurements were similar, or ‘homogeneous’ at a statistically significant level. The reason why the intra-class correlation was chosen here was because it is specifically adapted to compare data sets resulting from repeated measurements where the data sets represented the same ‘measurement class’. In this case the measurement class was scores in individual behavioural categories. An intra-class correlation could be understood as testing “the relationship among variables of a common class, which means variables that share both their metric and variance” (McGraw and Wong, 1996, p. 30). McGraw and Wong go on to state that the “intra-class correlation coefficients (ICCs) are alternative statistics for measuring homogeneity” (McGraw and Wong, 1996, p. 30). Thus, the intra-class correlation is based on slightly different assumptions compared to ‘inter-class’ correlations, such as the popular Pearson’s *r* correlation, where different measurement ‘classes’ such as length versus weight measurements are compared (McGraw and Wong, 1996).

In addition, for the case of testing intra-rater reliability, the intraclass correlation is ideally suited because it offers a specific intraclass coefficient for ‘single measures’ which specifically tests the consistency of repeated measurements where the data is collected by one single rater (Shrout and Fleiss, 1979). In this case, where one rater conducted the initial and repeated sets of measurements, the ICC model for ‘single measures’ assumes that inconsistencies rooted in the rater should be small (or fixed) and potential inconsistencies are more likely based in the rating system itself. Finally, the intraclass correlation offers to investigate the ‘absolute agreement’ between repeated measures, rather than focussing on the presence of a ‘linear relationship’, which is the case in the Pearson’s *r* correlation (Bland and Altman, 1986). According to Bland and Altman (1986, p. 3), “a change in scale of measurement does not affect the correlation, but it certainly affects the agreement”. Bland and Altman (1986) give one of multiple examples to exemplify such scenario: if a caliper took a measurement of two units of thickness and it would be plotted against half the caliper’s measurement, the data would still be related and even display a correlation of 1.0. Yet, the data points also displayed an agreement error since one data measurement would be double of that of the other. Focusing on agreement rather than linearity *per se* is therefore the preferred method to assess the ‘true value’ of reliability of the measurement data sets in this study.

In this study, an intra-class correlation was employed on the repeated analysis of 30% of the videos (10 videos in each of the two experimental conditions). The intra-class correlation compared the first round of video assessments of those ten videos with a second round of analysis of those videos. The intra-rater reliability test was conducted in each condition separately. In both cases, the intra-class correlation was conducted in IBM SPSS Statistics v20 utilising the appropriate ICC specifying ‘single measure’ at 95% confidence intervals. In addition to the chosen ICC for one single rater, it was opted to test for the absolute agreement between the measurement data sets since this was the purpose of this analysis. In order to obtain the second measurement data set, the initial investigator repeated the video analysis one week following completion of the first analysis.

To choose ten videos for the intra-rater reliability assessment, two sets of ten numbers (ranging between zero and thirty) were produced randomly using a free online software “*random.org: true number service*” (Haahr, 2010). One set of numbers was generated for each experimental condition separately. The recording sheets for the intra-rater test were the same utilised in the original video analysis. For the analysis, scores for the matched behaviours were compared as well as the scores for complete/mixed sequence and absence/presence of aberrant behaviours (Table 5.7). The intra-rater test was therefore conducted on the scores of the individual behavioural categories that were relevant for the assignment of the final fidelity code.

In order to prepare the data for intra-class correlation, the scores for each behavioural category were summed across the ten participants’ videos for both sets of repeated measurement sets (original analysis and repeated measurement set); the set-up can be viewed in Table 5.7. Scores for the individual 10 videos from each experimental conditions used for the intra-rater test can also be viewed in Appendix B1 and Appendix B2. An intra-class correlation was then calculated for the entire set of scores between the original video analysis and repeated measurement set within each experimental condition.

Table 5.7: For the intra-rater reliability test the scores for each behavioural category of demonstrated behaviours, as well as presence and absence of sequence and aberrant behaviours, were summed across ten randomly chosen participant videos in a test- re-test analysis. Within each experimental condition, an intra-class reliability test demonstrated a highly significant agreement between the test and re-test data sets.

		Imitation condition		**Emulation condition**	
		First analysis	Second analysis	First analysis	Second analysis
1.1)	Minimum six consecutive corners	6	6	0	0
1.2)	Other: minimum of three non-consecutive corners	4	4	3	3
2.1)	Minimum six consecutive margins	1	1	1	0
2.2)	Other: minimum of three non-consecutive margins	5	5	3	4
3)	Initial tip and base cutting	1	2	0	0
4)	30 sec scraping to remove foam	6	6	2	2
5)	Two repetitions of scraping and tip and base cutting	3	3	0	0
6)	Final shaping via scraping	7	7	3	3
	Mixed sequence	10	10	10	10
	Complete sequence	0	0	0	0
	Aberrant behaviour	10	10	10	10

In the imitation condition, the intra-class correlation calculated a strong agreement between the sets of scores in the test and re-test analysis (r (10) = 0.996, p = 0.0001); the strong correlation can be viewed in Figure 5.6. In Figure 5.6 it is obvious that even though there is an overall consistent agreement, the agreement is also not perfect as illustrated where slight deviations in the scores between the original and repeated data sets arose.

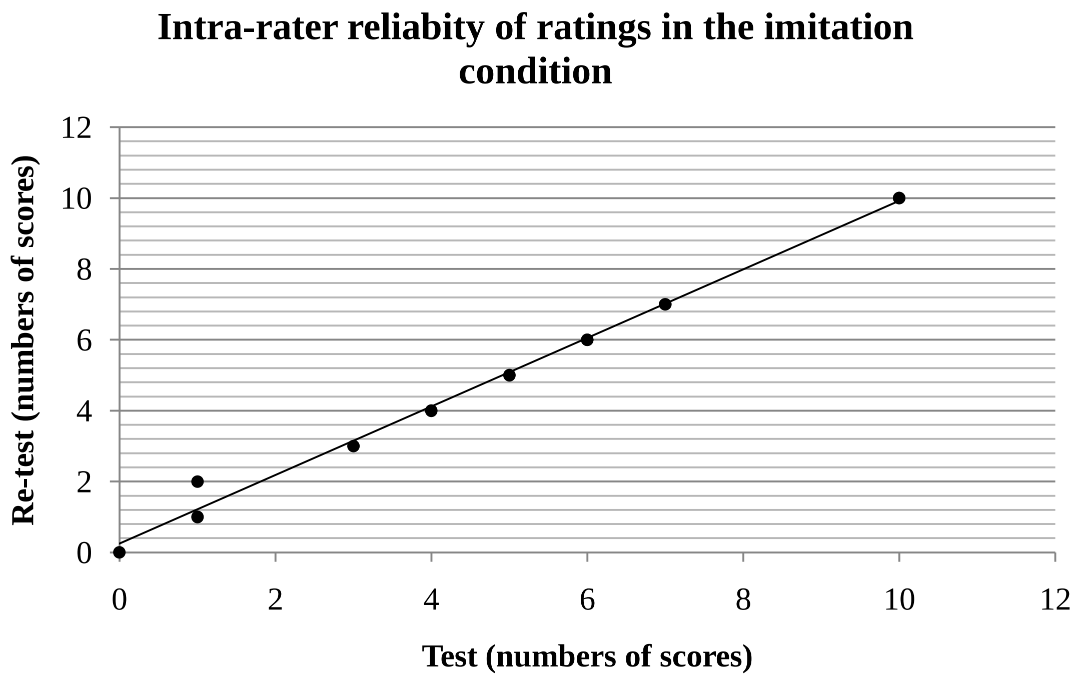

Figure 5.6: Intra-class correlation between the original video analysis and the repeated analysis in the imitation condition.

Similarly, the intra-class correlation established a high agreement between scores in the emulation condition at r (10) = 0.994, p = 0.0001). Again, Figure 5.7 illustrates the overall agreement but also shows that some inconsistencies are present between the original and repeated measurement sets. However, it can be confidently concluded from the intra-rater reliability test that, overall, the data retrieved from the video analysis was reliable.

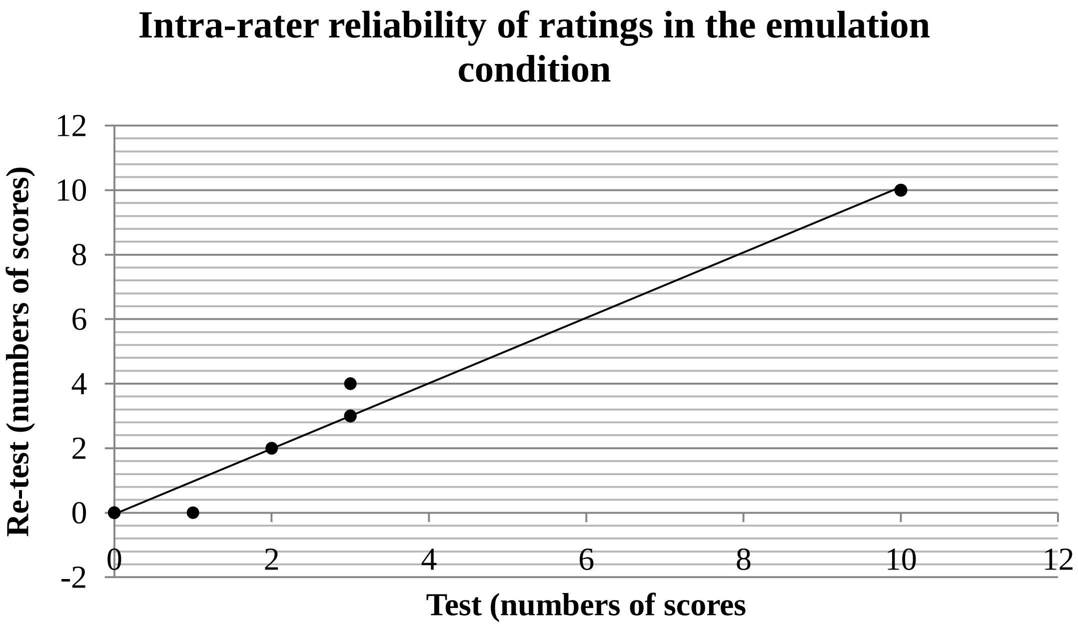

Figure 5.7: Intra-class correlation between the original video analysis and the repeated analysis in the emulation condition.

5.2.6 Statistical analysis

5.2.6.1 Analysis of shape copying error

For the analysis of shape copying error, all foam handaxe replicas were oriented according to the orientation protocol and underwent morphometric analysis and the size adjustment procedure relevant to extracting the shape data, as explained in Chapter 2. In addition, shape copying error for the two experimental conditions was also calculated precisely following the procedure as outlined in the methodology chapter (Chapter 3).

In a first statistical analysis, shape error rates between the imitation and emulation conditions were compared using a non-parametric Mann-Whitney *U* test because the shape error data did not pass normality tests. Both the Monte Carlo p-value (10,000 random assignments) and the asymptotic p-values were documented. The comparison of the rates of shape copying error was undertaken in PAST v2.17 (Hammer et al., 2001). All statistical tests for this study are reported at $\alpha = 0.05$.

5.2.6.2 Analysis of ‘fidelity codes’

To test whether participants in the imitation condition displayed a higher level of copying of the relevant manufacturing techniques compared to the emulation condition, the fidelity codes assigned to the videos were compared statistically between conditions. A Pearson’s chi-square test was used to assess whether participants contained fidelity codes to significantly different degree between conditions (n=30 in each condition). Thus, a Pearson’s chi-square test was applied on the fidelity codes in the original and also simplified versions of the coding systems. The Pearson’s chi-square tests were undertaken in IBM SPSS Statistics v20.

5.2.6.3 Analysis of ‘matched behaviour’ scores

The Pearson’s chi-square test was further supported by an additional quantitative analysis of the participants’ scores of matched behaviours between the imitation and emulation condition. The purpose of this analysis was to elucidate whether any effect for contrasting levels of behavioural matching would pertain when tested in isolation from the multi-dimensional fidelity coding system. Since the data failed normality tests, a non-parametric Mann-Whitney *U* test was used to compare the data statistically. The Mann-Whitney *U* analysis specifically tested whether the number of ‘matched behaviours’ were significantly different between the imitation and emulation conditions. The set of statistical analyses of the behavioural data was undertaken in IBM SPSS Statistics v20.

5.3 Results

5.3.1 Shape copying error

In the first part of the analysis the shape-error rates of all 42 morphometric variables were compared between the imitation and emulation conditions using a Mann-Whitney *U* test. In the imitation condition, shape error displayed a mean of 0.121 (SD = 0.05) and in the emulation condition the mean shape error was 0.137 (SD = 0.047); mean error bars are displayed in Figure 5.8. The list for the mean shape copying error rates for every morphometric variable within each experimental condition can be viewed in Figure 5.9 and figure 5.10. The Mann-Whitney *U* test demonstrated a significant difference in overall copying error rates for shape in the imitation condition compared to the emulation condition (*U* = 652, asymptotic p = 0.0393, Monte Carlo p = 0.0383). The test illustrated that participants created significantly less shape copying errors when they viewed the video in the imitation-learning context compared to participants in the emulation context. Mean shape error rates for the 42 morphometric variables between the two alternate conditions can be viewed in Figure 5.9 and Figure 5.10.

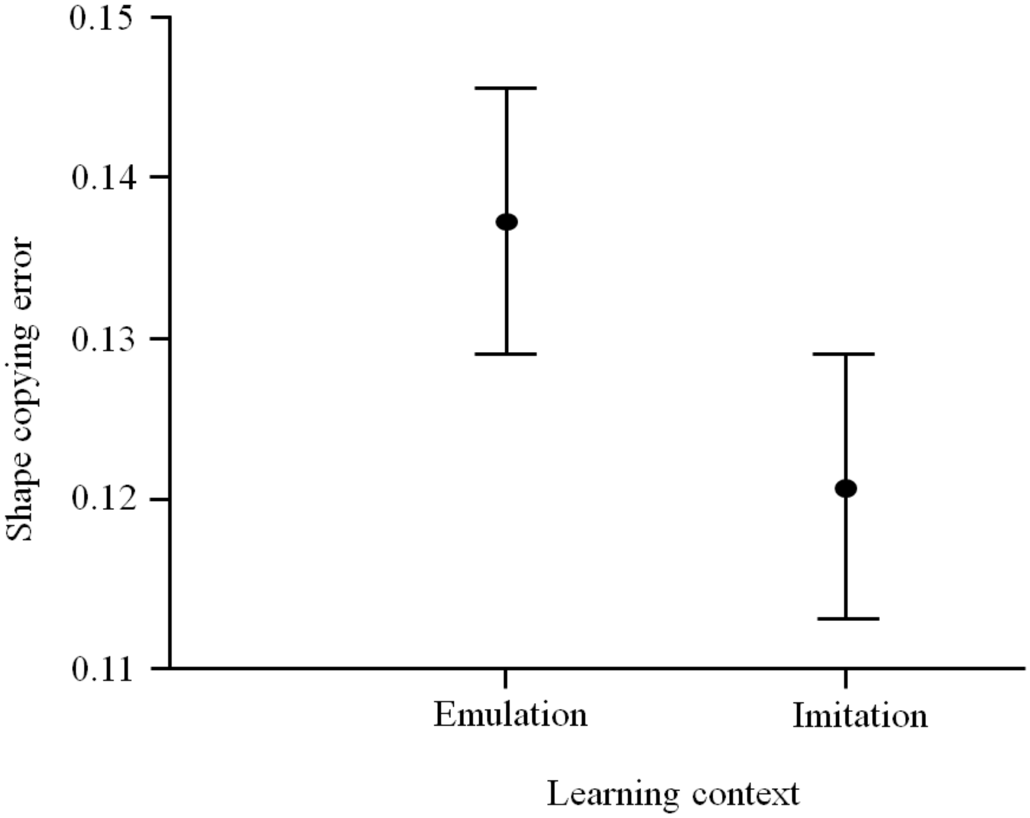

Figure 5.8: Error bars of mean shape error in the emulation and imitation conditions. Whiskers mark +/- one standard error.

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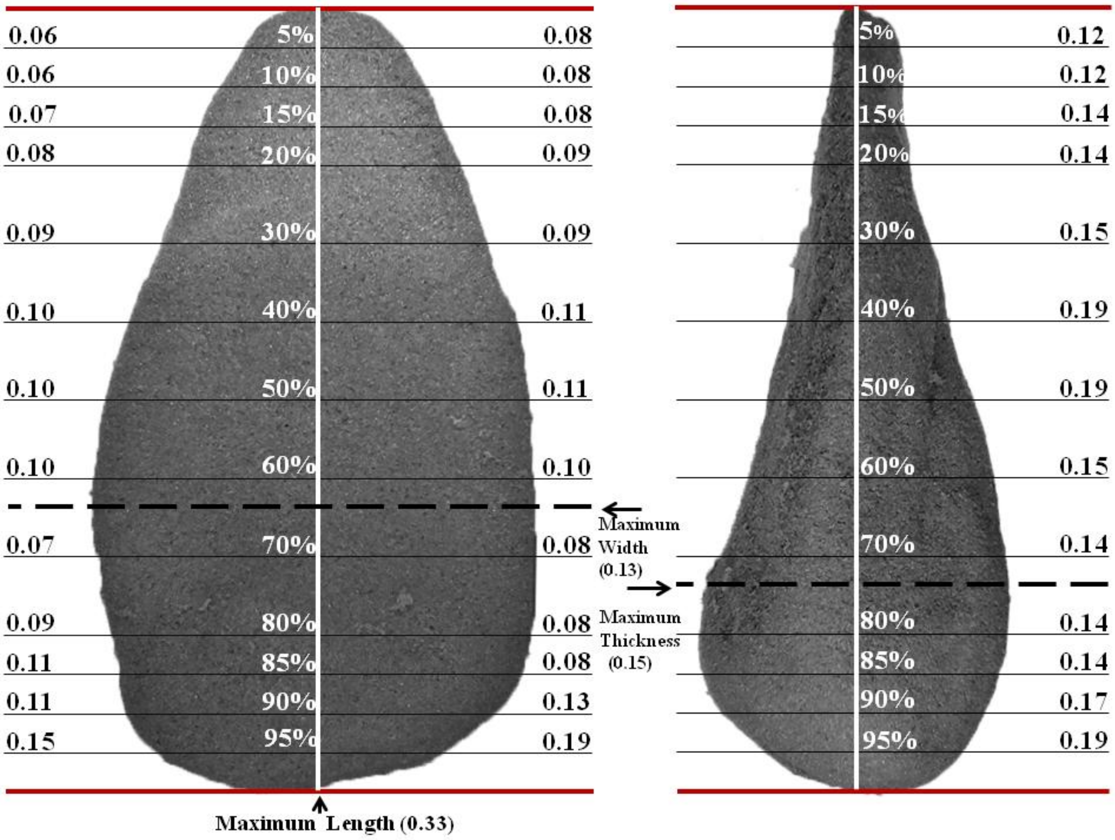

Figure 5.9: Mean shape error for 42 morphometric variables in the imitation condition.

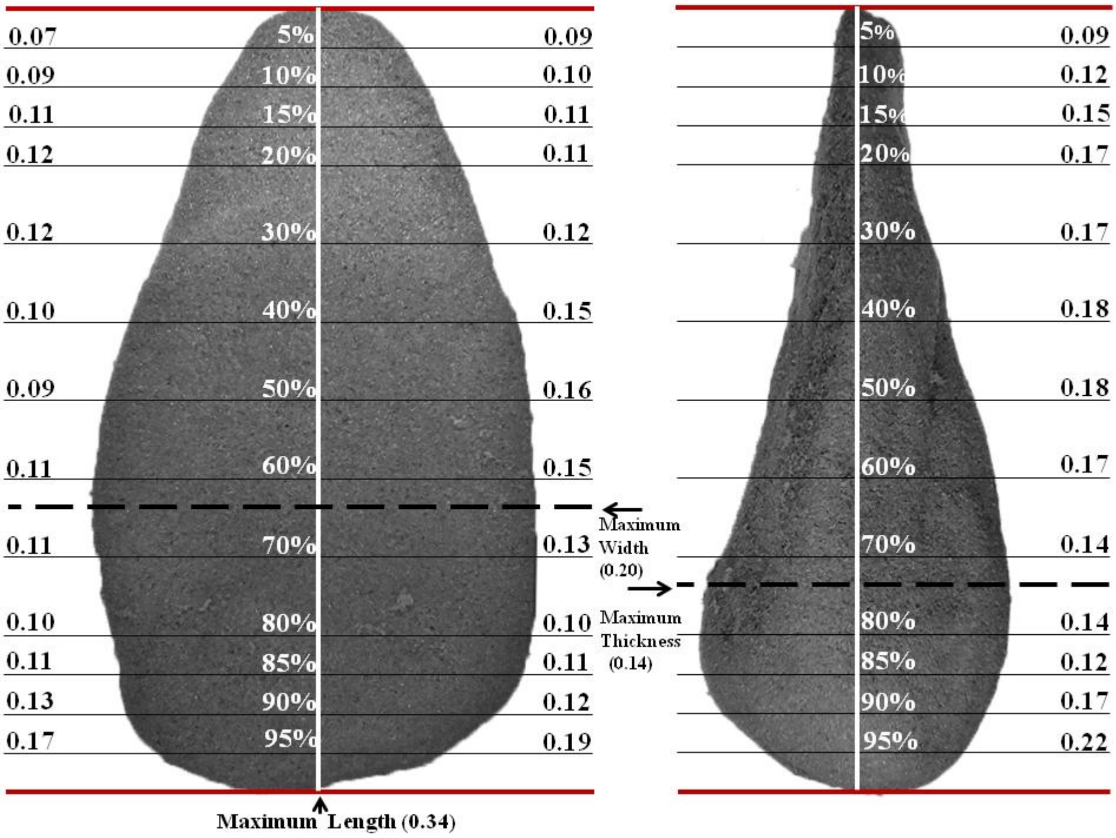

Figure 5.10: Mean shape error for 42 morphometric variables in the emulation condition.

5.3.2 Results from the main fidelity coding system

The majority of participants in both conditions scored between 0 and 5 fidelity coding categories. Since none of the participants in either condition scored in the highest two fidelity codes 6 and 7, this led to those two code categories to be removed from the chi-square analysis (Table 5.8). In addition, due to the low numbers of participants in code 5, the participant who scored in this category was merged with the lower-ranking fidelity code 4, resulting in the code category 5 to be collapsed with category 4. Therefore, contingency table for the chi-square analysis contained five fidelity copying categories (fidelity codes 0-4) versus the two learning contexts (imitation/emulation) (i.e., a 2×5 contingency table). In the statistical test assessing the main video analyses, a Pearson's chi-square test established a highly significant difference in the frequencies of the categories of fidelity codes between the two experimental conditions ($\chi^2 = 26.065$, DF= 4, n = 60, asymptotic p = 0.00003, Monte Carlo p = 0.0001). Given the high significance level, there is strong evidence that participants between the experimental conditions matched contrasting fidelity scores. The complete data of the individual fidelity scores in each condition can be viewed in Appendix B3. A better overview regarding the frequency distributions in the according fidelity scores can be viewed in Table 5.8.

Table 5.8: Percentages of participants that fit the respective fidelity codes of the main coding system in the imitation and emulation conditions.

Fidelity code	Copying behaviours	Emulation (in %)	Imitation (in %)
0	0 to 1 matched (plus aberrant behaviour)	66.67	10.00
1	1 to 2 matched (plus aberrant behaviour)	10.00	16.67
2	2 to 3 matched (plus aberrant behaviour)	16.67	16.67
3	3 to 4 matched (plus aberrant behaviour)	6.67	20.00
4	4 to 5 matched (plus aberrant behaviour)	0	33.33
5	5 to 6 matched (plus aberrant behaviour)	0	3.33
6	6 matched (mixed sequence)	0	0
7	6 matched (perfect sequence)	0	0

When considering the frequency distribution across the fidelity codes that represented higher levels of copying fidelity (Table 5.8), more than 50 percent of the participants in the imitation condition reached fidelity codes three to five. By reaching codes three to five, this meant that the majority of participants in this condition copied between three to six demonstrated behaviours. In contrast, only seven percent of participants in the emulation condition reached fidelity code three which means that they matched, maximally, three to four of the demonstrated behaviours. In this case, these seven percent of participants in the emulation context innovated behaviours such as those demonstrated in the video demonstration through individual learning. The pattern converses when considering the distribution across the fidelity codes reflecting lower levels of copying fidelity, such as codes zero and one. Codes zero and one represented the matching of zero to two demonstrated behaviours. Here, the majority of participants in the emulation condition (67%) were placed. In contrast, around 27% of participants in the imitation condition are found in these lower copying fidelity codes.

Therefore, these trends in the percentage rates reveal a clear pattern that the high significance level established by the Pearson's chi-square test arises from the fact that participants in the imitation demonstration matched the behaviours displayed in the video to a considerably higher degree compared to participants in the emulation condition.

5.3.3 Results from the 'simplified' fidelity coding system

In this coding system, the majority of the participants in both conditions fitted a fidelity code between 0 (low fidelity copying) and 2 (high fidelity copying). Only one participant in the imitation condition fitted code 3 (perfect fidelity copying) which means that this participant solely imitated the entire set of six behaviours. Given the low number in this code category, the participant was merged with the fidelity code below, therefore code 2. Thus, the highest fidelity coding category 3 was eliminated from the chi-square analysis. Therefore, the contingency table for this chi-square analysis was based on the three fidelity codes 0, 1, 2, which equalled low, medium and high levels of copying, versus the two learning contexts imitation versus emulation (i.e., 2×3 contingency table). Subject to the chi-square analysis, participants in the two learning contexts matched distinct fidelity codes at statistical significant level (χ^2 = 19.147, DF= 2, n = 60, asymptotic p = 0.00007, Monte Carlo p = 0.0001). The distribution of the frequencies of matched behaviours in the fidelity codes between the different learning contexts are displayed in Table 5.9. Similar to the main coding system, this simplified coding system led to a similar statistically significant result, which illustrated that the majority of participants in the emulation condition fitted lower fidelity codes, for example, 76.67% of participants fitted the lowest fidelity code 0. By contrast, the majority of participants in the imitation condition were based in higher-ranking fidelity codes 1 and 2 (e.g., a sum of 73.34% scored in one of those two codes). This second analysis therefore confirms that an alteration of the coding system still generates similar statistical effects, therefore strengthening the fact that the main coding system effectively reported evidence for imitation.

Table 5.9: Percentages of participants that fit the respective fidelity codes of the alternative and simplified version of the coding system in the imitation and emulation conditions.

Copying fidelity code	Manufacturing techniques copied	Emulation (in %)	Imitation (in %)
3	6		
2	5 or 4	0	36.67
1	3 or 2	23.33	36.67
0	1 or 0	76.67	26.67

5.3.4 ‘Matched behaviour’ scores

In the final step of the behavioural analysis, the differences in the scores of matched behaviours between the experimental conditions were assessed more closely. Figure 5.11 shows that the percentage of people in the imitation condition copied the six demonstrated behaviours to considerably higher degree than participants in the emulation condition. Note that scores from the two behavioural subcategories for removing corners and margins were merged into one for each of the behavioural criteria to facilitate the data analysis. The merged behavioural categories incorporated the possibilities of cutting three to six corners or margins.

When averaging the scores for all participants in each condition across the six demonstrated behaviours, participants in the imitation condition scored an average of 3.533 matched behaviours (SD = 1.408). Participants in the emulation condition had a mean score of 1.233 matched behaviours (SD = 1.331). When comparing the different individual scores for all six behaviours between the two experimental groups, a Mann-Whitney *U* test established that participants in the imitation condition copied significantly more of the demonstrated manufacturing techniques compared to participants in the emulation condition (Mann-Whitney *U* test: *U* = 115; n_1 = 30; n_2 = 30; asymptotic p = 0.0001; Monte Carlo p = 0.0001).

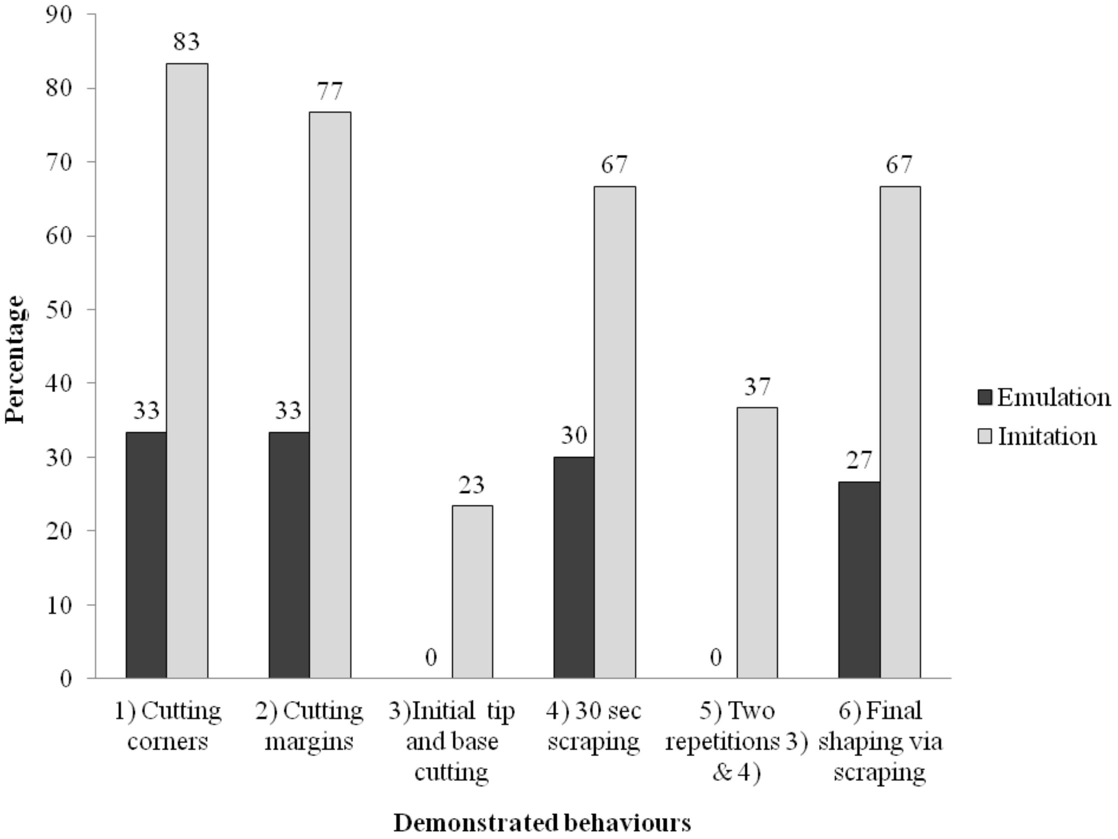

Figure 5.11: Distribution of participants in the imitation and emulation conditions engaging in the six categories of matched behaviours.

Thus, the additional quantitative analysis on the actual scores in the matched behaviour categories confirmed that participants copied demonstrated behaviours comparatively more so than participants in the emulation condition.

Altogether, the results of this experiment demonstrated that participants in the imitation condition generated significantly lower levels of shape error, compared to the emulation condition. It could also be demonstrated that the low rate of shape error in the imitation condition was associated with participants copying demonstrated manufacturing techniques significantly more so than participants in the emulation condition. Thus, it could be verified that differences in the shape error rates between the two conditions could be confidently traced to the differences in the learning context.

5.4 Discussion

Recent experimental and ethnographic studies suggest that distinct individual-level social transmission processes generate different patterns of variation in material culture, which affect the evolution of detectable morphological attributes on the population-level (Bettinger and Eerkens, 1999; Mesoudi and O'Brien, 2008a; Kempe et al., 2012). In the last two decades, research from the comparative psychology literature has emphasized the study of distinct social learning processes in the quest for the specific conditions required for the 'heritable continuity' underlying the emergence and long-term preservation of cultural traditions (Boyd and Richerson, 1985; Tomasello, 1993; Whiten et al., 2009b; Galef, 2012). It is due to the 'complete' transmission of manufacturing techniques *and* end-state product that imitation is argued to contain the capacity to considerably reduce variation-generating rates of cultural mutation which threaten to erode emerging patterns of artefactual traditions (Shea, 2009). Conversely, emulation is often assumed not to be capable of transmitting cultural modifications at the level of copying fidelity required to maintain 'artefactual traditions' over the long-term, because only the end-state is copied rather than the exact behavioural patterns involved (Tomasello, 1999; Whiten et al., 2004, 2009b). For this reason, emulation has been hypothesized of potentially incapable of sufficiently impeding rates of 'cultural mutations' to explain the long-term preservation of lasting artefactual 'traditions' in the archaeological record (Shea, 2009).

Here, it was tested whether two contrasting social learning mechanisms, imitation versus emulation, differentially impact the rate of shape copying error in an experimental design where size-adjusted shape data was analysed from experimentally produced foam handaxe replicas. Participants were required to faithfully copy a foam target handaxe in two different social learning contexts. In the 'imitation condition', participants were shown both the live model of the target handaxe form and a video demonstration that presented the sequence of manufacturing techniques employed in its production. Participants in the 'emulation condition' were only shown the end-state of the target form. Consistent with the theoretical predictions, the first set of statistical analyses illustrated that foam handaxe replicas produced by participants in the imitation learning context resulted in significantly reduced shape copying error rates compared to those foam replicas produced in the emulation learning context. A second set of analyses confirmed that participants in the imitation condition matched the manufacturing techniques demonstrated in the video at a significantly higher degree compared to the participants in the emulation condition, providing further direct evidence that participants in the imitation condition engaged in high-fidelity copying of the action sequences displayed in the demonstration.

A fidelity coding system was developed specifically for this study to assess the level of imitation participants employed in multiple behavioural categories between the two experimental conditions. On the basis of this video analysis it could be established that participants in the imitation condition matched the manufacturing techniques to significantly higher degree compared to the emulation context. This is a highly relevant finding because it indicates that imitation (copying of the actions seen in the video) was indeed the key factor leading to lower copying errors in the imitation condition, compared to the emulation condition. Therefore, the possibility that factors other than imitation might have explained the statistical difference in shape copying error could be directly and confidently eliminated.

Therefore, within an explicit experimental framework, this study provided conclusive evidence for the hypothesis that imitative learning, the goal-directed copying from a model's manufacturing techniques, can significantly reduce shape copying error compared to a contrasting social learning mechanism where the manufacturing techniques are not directly copied. These findings suggest that imitation has the capacity for high-fidelity copying and so would better ensure the preservation of detailed morphological manifestations (i.e., 'hereditable continuity'), underlying phylogenetic lineages of 'shaped' artefactual traditions. The results further suggest that in the absence of high-fidelity copying of *manufacturing techniques*, the cultural mutation rate in the shape morphology of cultural artefacts is considerably higher, which potentially renders 'emulated' cultural traditions relatively unstable over the course of cultural transmission.

On the basis of the video analysis it should be noted that despite the significant differences in copying fidelity between the distinct learning contexts, Table 5.8 illustrated clearly that participants even in the imitation condition failed to copy the entire set of behavioural demonstrations. In addition, most participants who have seen the video also engaged in aberrant behaviours such as innovative uses of the plastic knife or behavioural modifications of the techniques demonstrated. A few explanations and implications regarding these observations may be suggested. First of all, in the light of the experimental set-up, it can be noted that participants were given only one opportunity to view the video demonstration. This may have impacted memory recall to some extent and may explain why participants in the imitation condition did not copy all behaviours perfectly. In addition, participants in the imitation-context faced the additional challenge of being confronted with a novel task of faithfully copying a 3D object, for which they were not given any previous practice trials or any form of preparation other than watching the video. This lack of training likely posed additional challenges which raised the difficulty of achieving the highest (theoretical) fidelity score. In addition, there is also the possibility that participants deliberately engaged in novel behaviours in the attempt to complete the task to the best of their abilities. These different factors considered the results of the video analysis present a realistic evaluation of the level of imitation that participants engaged in when exposed to single demonstrations of a sequence of manufacturing techniques. Importantly, the analysis illustrates that while participants in the video condition did not perfectly copy all the behaviours demonstrated, they clearly engaged in imitative learning *sufficiently* more so compared to participants who have not viewed the demonstrations, to significantly reduce copy-error rates. In other words, the results from the video analysis demonstrated that the *tendency* toward higher copying fidelity induced by imitative learning was sufficient to generate statistically significant effects, *even* despite the fact that participants in the imitation condition did not copy ‘perfectly’.

The findings of this research experiment also have direct implications with regard to the social mechanisms required for the emergence and perpetuation of some the earliest of prehistoric artefactual traditions. The Acheulean is also famous for its imposition of high congruence in shape over time and space (Gowlett, 1984; Wynn 2002; Petraglia et al., 2005). It is sometimes argued that social learning with high copying-fidelity was required for such high level of homogeneity in shape to persist (Wynn, 1993; Mithen, 1999; Lycett and Gowlett, 2008). The results of this study support the idea that imitation could have been a means by which stability in shape traditions can be maintained, especially in the face of relatively high copying errors (i.e., ‘mutation loads’) that are likely to accompany such ‘reductive’ processes of manufacture (Chapter 3). Hence, these findings suggest that besides sophisticated cognitive capacities (i.e., foresight and coordination in action planning) hominin stone-tool manufacturers had likely acquired the capacity for complex social learning mechanisms such as imitation to obtain the manufacturing skills necessary for the cultural continuity of the Acheulean across time and space (Wynn, 2002; Stout et al., 2008; Stout, 2011; Vaesen, 2012).

The study of social learning and high fidelity copying may also be particularly relevant to the question regarding the presence of distinct manufacturing ‘traditions’ in material culture. Despite the overarching form standardisation in the Acheulean, handaxes have been shown to exhibit regional variability, possibly associated with distinct traditions within the Acheulean, at least statistically speaking (Wynn and Tierson, 1996; Lycett and Gowlett, 2008). Therefore, the findings in this study suggest that imitation may have played an essential role explaining the roots of the within-population convergence and between-population divergence (Whiten et al., 2005). Notably, Whiten et al. (2005) have explored this notion with an experimental approach using non-human chimpanzees (*Pan troglodytes*). The study illustrated that when two chimpanzee models from two separate populations were trained on a different tool-use technique to extract food rewards from the same ‘panpipe’ apparatus, other members of the two populations copied the technique introduced by the model in an open diffusion approach when the models were reintroduced to their populations. It was evidently demonstrated that alternate tool-use techniques spread in the two separate chimpanzee populations because members of each population adopted the behavioural variant as demonstrated by the model. These studies illustrate that traditions mediated through social learning mechanisms shared by members of the population are maintained and spread by within-group fidelity of shared techniques. Behavioural variation can therefore be “explained as innovations that arise with varying probability in a population and are then spread and maintained with varying probability by social learning” (van Schaik, 2009). Importantly, these experiments on behavioural variation in chimpanzees (Whiten et al., 2005; Horner et al., 2006), together with recent approaches employing phylogenetic methods (Lycett et al., 2007) and recent ethnographically based studies (Hobaiter et al., 2014; van Leeuwen et al., 2014) illustrate that transmission by social learning is likely the key factor in the generation of patterns of between-group variation and spread of innovations in the absence of ecological and genetic factors. These approaches highlight that social transmission events accounting for within-group convergence and between-group divergence can explain the vast diversity of social and tool-use behaviours recorded in wild chimpanzees (Whiten et al., 1999; Boesch and Boesch, 1990; McGrew, 1992; Boesch, 2003). It is not an improbable implication that social learning processes that incorporate the copying of behavioural factors (i.e., manufacturing techniques) as well as the end-state product such as imitation, may have played an unprecedented role in establishing stable, detectable patterns of variation and diversification, which have led to statistically traceable differences in material traditions in early artefactual culture manufactured by hominin ancestors (e.g., Wynn and Tierson, 1990; Lycett and Gowlett, 2008).

To conclude, this experiment explored empirically whether different social learning mechanisms, such as imitation (copying of actions that lead to an end-state product) and emulation (copying an end-state product without the behaviours that lead to it) generate distinct patterns of variation in the archaeological record. The results illustrated that participants created significantly less shape copying errors when they viewed a video with a demonstration of relevant manufacturing techniques employed to produce the target foam model, as opposed to just viewing the end-state target form. In addition, it was demonstrated that participants in the imitation condition copied the action sequences displayed in the demonstration significantly more so compared to participants in the emulation condition. The latter analysis verified that differences in shape error rates could be confidently attributed to differences in the learning context. One of the main implications derived from these results is that imitation may be imperative for the long-term perpetuation of visibly distinct archaeological traditions underlying artefactual lineages directly because it has the capacity to sufficiently ‘reduce’ mutation loads that are detrimental to their maintenance.

Chapter 6 - The impact of differences in the mode of manufacture on shape variation in cultural artefacts: can contrasting tool traditions create distinct shape manifestations?

6.1 Introduction

The study of microevolutionary processes that affect long-term changes in the variation of artefact assemblages, such as guided variation, cultural selection biases like prestige (Henrich and Boesch, 2011; Cladière and Whiten, 2012), or conformity (Henrich and Gil-White, 2001; McElreath et al., 2005; de Waal, 2013) as well as social learning mechanisms (e.g., Galef, 2012; Heyes, 2012; Whiten et al., 2004, 2005) have gained increasing focus in the research literature. In addition, changes in the frequency of cultural variants by drift mechanisms are central to the understanding of the fundamental processes describing how variation in cultural information spreads and diversifies (Shennan, 2008a, 2011).

As noted earlier (Chapters 1 and 3), to date, few experimental attempts have been made to study such microevolutionary effects that actually influence patterns of artefactual variation at the proximate level. Utilising experimental and also computer-simulation frameworks, recent research attempts have investigated how unintentional copying error becomes introduced into material culture production and how such error ultimately generates distinct patterns of artefactual variation. Eerkens (2000) established that copying error can be introduced as a result of memory effects. Other recent investigations have also illustrated that copying errors are generated as a result of perceptual limitations of detecting differences between similar objects below a specific size threshold (Eerkens and Lipo, 2005). Hence, humans appear to fail to detect variation in size variation below 3%, a limitation known as the ‘Weber Fraction’, allowing small-scale copying error to be introduced that falls below such perceptual ‘thresholds’ (Eerkens and Lipo, 2005; Kempe et al., 2012).

At this point, it is perhaps necessary to review the previous studies in this thesis, since (inevitably) the distinct elements of the experimental framework developed up to this point may now begin to relate to each other, both in conceptual and practical terms. Based on the increasing insight that the study of copying error, which are defined as a form of 'cultural mutations', is valuable in respect to cultural evolutionary models, the experiments described thus far in this research project were ultimately concerned with the discovery how 'cultural mutations' introduced during the manufacturing process manifest in shape attributes of cultural artefacts. Given that unintentional copying error can impact longer term artefactual change, it is important to empirically test how factors related to the manufacturing process can cause such sources of variation. Using a unique experimental framework, based on the analysis of metric shape attributes of experimentally produced 'Acheulean' handaxes, the study of unintentional copying error that is introduced in manufacturing processes has been investigated via a series of experiments performed under controlled laboratory conditions.

The first experiment in this thesis (Chapter 3) investigated whether rates of shape copying error were affected differently in reversible, or 'additive-reductive' manufacturing traditions such as basketry and pottery (where material can be both added an removed) as opposed to irreversible or 'reductive-only' traditions, such as stone-tool knapping (where material can only be removed). The premise of the study was based on Deetz (1967) hypothesis that for reductive-only traditions, errors introduced during the production process are largely irretrievable and generate larger amounts of variation compared to additive-reductive processes, where errors are more readily reversed. This hypothesis was tested on metric shape data obtained from 60 plasticine 'Acheulean' handaxe replicas, each of which was produced by a different participant (n=60). For the production of the foam handaxe replicas, participants were asked to copy the shape data from a target flint replica from a standardised block of plasticine using a simple steel table knife. In the 'reductive-only' condition, participants could only remove material but were not permitted to add material onto their replica. Conversely, participants could both remove and add plasticine during the copying task in the 'additive-reductive' condition. The results demonstrated that reductive manufacturing traditions, such as stone-tool production, generate cultural mutation rates in shape attributes at significant higher levels, in statistical terms, compared to additive-reductive manufacturing traditions. This finding supported Deetz' initial assumption that different manufacturing processes generate distinct levels of variation. In summary, the results illustrated that rates of cultural mutations are process dependent: reductive manufacturing traditions such as stone knapping carry an inherently larger mutation load compared to other forms of reversible manufacturing processes. While such high mutation rates have important consideration for the 'evolvability' of cultural evolution (Chapter 3), there is also an increased potential that cultural traditions face erosion in the long-term (Chapter 5). Hence, where standardised shape traditions are prevalent in the long-term in reductive manufacturing traditions, these may require the implementation of specific 'fidelity mechanisms' to counteract such high mutation rates.

In the second experiment (Chapter 4) it was investigated how multiple varying constraints that act on the production time of manually manufactured artefacts affect the production of rates of shape copying error. The notion that time constraints can impact on shape variation has not been rigorously explored previously within an experimental framework. This is despite general consensus in the research literature that time constraints are important pervasive factors affecting tool production and hunter-gatherer economy (e.g., Binford, 1978, 1979; Torrence, 1983; Rasic and Andrefsky, 2001; Ugan et al., 2003). Using an experimental set-up similar to the previous experiment, participants were asked to copy the shape of a model target form. In this experiment, it was tested whether systematically reducing the production time would lead to a proportional increase in mean error rates or, alternatively, whether changes in the rates of shape copying errors were best explained by reaching a 'threshold'. Here, 90 participants copied the shape of a foam model handaxe using a machine pre-cut standardised foam block and a plastic knife. In three experimental conditions, participants were provided with 20, 15 or 10 minutes to manufacture their handaxes (n = 30 in each condition). While there was no a statistically significant difference obtained between the 20 minute and the 15 minute time conditions, there was a significant difference obtained between the 20 minute and the 10 minute time conditions. This finding suggests that copying errors might be best modelled according to a 'threshold' effect. In addition, the results of this experiment illustrated that time constraints play an important role in the generation of variation during artefactual production. Therefore, time constraints on the time provided for manual manufacture should be incorporated into models of cultural evolution.

The third experiment in this project (Chapter 5) was concerned with the study of how and whether distinct mechanisms of social learning differentially affect rates of cultural mutations. There is general agreement in the research literature, that only higher fidelity copying mechanisms such as imitation can generate low patterns of variation that maximise the potential for long-term perpetuation of cultural traditions (e.g., Shea, 2009; Mesoudi et al., 2013). Conversely, lower copying fidelity mechanisms such as emulation generate high levels of variation that potentially ‘erode’ cultural traditions over the long-term. The study’s main endeavour was to shed light on which forms of social learning could sufficiently explain the maintenance of long-term shape traditions in artefact culture, such as frequently implied in the perpetuation of, for example, handaxe industries produced during the ‘Acheulean’ (Lycett and Gowlett, 2008). Imitation was defined as the copying of manufacturing techniques involved in the production of a specific end-state product. Emulation was defined as learning about an end-state product without actually copying the behaviours that lead to the product. This experiment tested the assumption whether imitation generates statistically significantly less shape error rates compared to emulation, provided that imitation is associated with the more ‘accurate’ copying mechanisms. In this experimental context, 60 participants copied the shape of a target foam model using a standardised foam block and a plastic knife. In the emulation condition (n=30), participants were provided with the end-state product. In the imitation condition, participants (n=30) were supplied with the end-state target form as well as a video demonstration that showed six successful manufacturing techniques employed in the production of the target form.

Results of this latter study (Chapter 5), provided evidence that imitation significantly reduces rates of cultural mutation in shape attributes compared to emulation. In addition, a video analysis of each participant’s manufacturing process demonstrated that participants in the imitation condition copied the manufacturing techniques significantly more so compared to the emulation condition. Therefore, the findings illustrate that participants in the imitation condition were more accurate in the copying task, compared to participants in the alternate condition, because they imitated the demonstrated manufacturing techniques. Even though the copying process was not ‘perfect’ e.g., only a minority of participants in the imitation condition copied all demonstrated manufacturing behaviours, even ‘imperfect’ copying was sufficient to significantly reduce rates of cultural mutations compared to emulative learning. The study highlights that high fidelity copying mechanisms, such imitative learning, may counteract ‘cumulative copying error’, as demonstrated by Eerkens and Lipo (2005) and Kempe et al. (2012).

These three experiments have shown, therefore, that differences in various factors surrounding the manual manufacture of material artefact traditions can each have considerable impacts on artefactual attributes. Moreover, such sources of variation introduced during the manufacturing process can have implications that need to be considered in cultural evolutionary models. For example, the experiment reported in the preceding chapter on the impact of different fidelity copying mechanisms, specifically highlights the importance of the relevance of instigating fidelity mechanisms in establishing sustainable long-term cultural traditions where shape maintenance in material cultural traditions might be of particular bearing.

One factor that has not yet been discussed in the context of these experimental endeavours is the question of *to what extent cultural mutation rates reflect subtle differences in the 'equipment' applied to the experiments of this type?* In the previous experiments, the main mode of manufacture was a cutting tool, such as the steel knife in the first experiment (Chapter 3), and the plastic knife used in the foam-cutting experiments (Chapters 4 and 5). There are two distinct reasons why considering further—in explicit experimental terms—the effect of manufacturing equipment on artefactual variation is important. One reason is methodological in the context of the experimental programme initiated here in this dissertation, while the other has wider theoretical and practical implications for the evolutionary modelling of material culture change. These two distinct sets of motivations for experimentally assessing the practical effects of equipment/tool differences in experiments of this type are discussed in turn below.

In the experiments investigating the effects of different time constraints and learning contexts on variation, the mode of manufacture was a plastic knife. One reason why the investigation of the impact of differences in the 'mode of manufacture' on copying error could have important implications within the context of this thesis, is the conditions required for enhanced control and replicability within the experimental settings. The concept of 'equipment' might be relevant where the study of manufacture-related factors is of particular focus, as is the case in these experiments. As discussed in Chapter 1, experimental investigations contain the overarching advantage of maintaining high levels of 'internal validity' which relates to the aspect that experiments facilitate control over environmental or 'external' factors within a laboratory setting (i.e., keeping experimental conditions equivalent) (Mesoudi, 2011; Lycett and Eren, 2013). In this respect, the investigation of whether subtle changes in the equipment used in the experimental setting can be a potential source of variation could lead to important methodological insights. This is because if there are subtle changes in the equipment employed in the manual manufacture of experimentally produced artefacts, these equipment-related changes are likely to generate distinct levels of variation, and consequently alter the results. Hence, in regards to the overall aims of this dissertation (i.e., in terms of establishing the importance of an experimental programme studying the microevolutionary sources of artefactual variation), it is important to understand whether and how changes to the equipment, such as the mode of manufacture, impact rates of shape copying error. For instance, it may be vital to properly evaluate and anticipate changes in the experimental set-up to appropriately validate study outcomes where changes to the equipment have been made.

In addition, the question of how differences in the mode of manufacture impact on material culture has previously been deemed important in regards to the formation of the archaeological record (e.g., Foster, 1960). In the context of an evolutionary framework, ‘input behaviours’ underlying patterns of artefactual variation—such as manufacturing method/equipment—might themselves arguably become a target of cultural selection, especially if distinct sets of equipment are more likely to reduce copying error rates and thus increase trait fidelity over time. In other words, considering this factor in explicit terms is important in the context of wider questions of long-term cultural change, especially for evolutionary approaches.

Notably, differences in manufacturing equipment may have been an important dynamic since the earliest elements of the archaeological record. Consider, for example, the fact that different knapping tools were utilised in the production of different sets of stone tools during the Palaeolithic (Schick and Toth, 1993; Inizan et al., 1999; Costa et al., 2001). Examples of different equipment used for manufacture are often highlighted in respect to different percussion techniques used during the reductive stone knapping processes. Percussion is a technique referred to as “application of force to fracture raw materials” (Inizan et al., 1999, p.30). Variations of direct percussion techniques such as use of ‘hard hammer’ versus ‘soft hammer’ percussion were applied by hominins during the production of Acheulean stone tool technologies, for example (Schick and Toth, 1993; Roche, 2005). Hard hammer percussion was a stone knapping technique employed by hominin tool makers around 2.5-1.5 million years ago (Schick and Toth, 1993). During the manufacturing process, one stone, a round or egg-shaped hammer stone was used as the ‘mode of manufacture’ (Wenban-Smith, 1989). The hammerstones used were generally harder or equally hard as the core stone. The hammerstone is hit against another which represents the ‘core’. During the percussion process, flakes are removed as part of the knapping process. According to Roche (2005, p. 36), “in the case of stone knapping, even for the most basic *chaîne opératoire*, the hammerstone is an intermediary tool, which enables the knapper to fracture the raw material whose fragments will themselves in turn become tools”.

‘Soft’ hammer percussion is associated with the utilisation (as a hammer) of material softer than the stone being knapped. Compared to tools used in hard hammer percussion, ‘soft’ hammers can consist of antler, bone, softer types of stone (e.g., sandstone), ivory or wood. Different parts of bones, such as thick cortical bone or articular ends, foot bones and fragments from large mammalian bone, believed to have been utilised for such purposes, have been found at archaeological sites together with stone tool artefacts (e.g., Stout et al., 2014, p. 580). It is assumed that soft hammer percussion was introduced considerably later than the introduction of hard hammer percussion, perhaps around 500,000 years ago (Schick and Toth, 1993; Soressi and Dibble, 2003; Roche, 2005), although, of course, biases against preservation of soft hammers made of organic material may be leading to considerable underestimation of such practices in earlier phases. Evidence of stone tool knapping activities via soft hammer percussion has been collected at archaeological sites such as Boxgrove (West Sussex) in southern England, where soft hammer tools such as antlers were found alongside stone tool artefacts (Stout et al., 2014; Wenban-Smith, 1989). In their recent archaeological investigation of Boxgrove, Stout et al. (2014, p. 587) described how the antlers recovered contained scrape marks associated with “periosteum removal and/or surface preparation”, and removal of brow and bez tines. Therefore, these antlers were assumed to have been purposefully modified into ‘percussors’ for the knapping process.

The question whether the distinct modes of manufacture, such as soft as opposed to hard hammer percussion, generate distinct effects on artefactual attributes such as flake tools has been investigated within experimental contexts (e.g., Newcomer, 1971; Speth, 1975; Pelcin, 1997; Wenban-Smith, 1989; Driscoll and García-Roja, 2014). Pelcin (1997), for example, used an experimental apparatus where he tested whether antler hammers utilised as ‘soft’ hammer percussion tools, which were applied to a standardised glass block to remove flake tools, affected flake attributes (e.g. flake ‘length’) differently compared to steel hammers applied as ‘hard’ hammer percussors. Pelcin’s (1997) study showed that differences in flake attributes were explained by the different techniques applied by different knappers, as opposed to distinct modes of manufacture, or ‘percussors’. Most recently, Driscoll and García-Roja (2014) also compared effects of soft versus hard hammer percussion. Similar to Pelcin (1997), the aim of the experiment was to test the effects of soft versus hard ‘indentors’ on flake attributes. In their study, two knappers used antler and limestone hammers as ‘soft’ percussion tools versus granite hammer stones as ‘hard’ hammer tools. Both tools were used to produce flakes from chert nodules. While both study examples by Pelcin (1997) and Driscoll and García-Roja (2014) did not demonstrate strong evidence that subtle differences in the mode of manufacture generated distinct effects in terms of flake attributes, these studies represent determined advances to specifically investigate whether and how differences in mode of manufacture impact upon attributes in the artefactual end-product.

Different modes of manufacture involving differences of tools/equipment are also known in the production of other prehistoric artefact traditions such as pottery production. Orton et al. (1993, p. 117), for example, summarise principal pottery forming methods into two categories. One formation tradition is termed ‘hand-formation’ which is defined as a mode of manufacture without the use of centrifugal force. The second method of pottery production involves a rotating wheel which is referred to as ‘wheel-throwing’ (Blackman et al., 1993; Roux, 2010). Unlike hand formation traditions, the wheel-throwing technique employs “centrifugal force as an active agent in the forming and shaping of the vessel” (Orton et al., 1993, p.117). During wheel-throwing, clay is modified in the centre of a wheel table which is rotated horizontally. While the wheel rotates, the clump of clay is pulled upwards and shaped into the desired pottery forms using the hands and can be modified into various shapes and forms. Alternate traditions of the wheel-throwing technique are known to the archaeological record. The most basic distinction in wheel-throwing is the tradition of using a single wheel as opposed to a double wheel, with each wheel-throwing tradition containing its own structural and operational idiosyncrasies (Orton et al., 1993). Alternative variants of pottery production using centrifugal force other than the wheel may also incorporate the use of a lathe. Lathe production contains a set-up where clay is modified by placing it around a mould which is incorporated into a rotating rod that rotates the pottery artefact vertically on its axis. Randall-MacIver (1905, p. 23-25) described lathe production in the following terms:

> "*Two boards are set up vertically about 15 inches apart on a wooden base, and held together by two horizontal struts. From the tops of the boards two pieces of iron project horizontally inwards and form the pivots, on to which a thin rod some 10 inches long is slipped. This rod is rotated by a bow about 30 inches long, which the operator works with one hand, while with the other he shapes and graves the clay as it revolves. The meaningless lump on the lathe rapidly acquires an outline under the skilful direction of the potter*".

Cultural variants in manufacturing traditions using 'hand formation' techniques are known as 'coil' or 'slab' method (Smith, 1978; Orton et al., 1993; Tite, 1999; Roux, 2010) but other manual methods have been described by ethnoarchaeologists (e.g., Foster, 1960; Arnold, 1991; Arnold and Nieves, 1992; Orton et al., 1993). During coiling, pottery artefacts are assembled by rolls of clay which are placed on top of each other to form desired pottery shapes. In the slab method, artefact fragments are produced where pieces of clay are flattened out evenly and are later assembled by squeezing them together to form the pottery artefact (Orton et al., 1993). Other hand formation traditions even involve the use of tools such as marine shells which are utilised for the thinning and lengthening of pot walls. The use of shells as tools of manufacture has been observed, for example, in pottery production in Nubia, Egypt (Randall-MacIver, 1905). Some traditions include the use of moulds, where clay is pressed manually against the moulds to obtain their form and structure (Randall-MacIver, 1905; Foster, 1960).

These numerous manufacturing traditions emphasise the central role that the concept of 'equipment' plays in the production of artefact traditions. However, it is also demonstrated that there is a high variability in the equipment employed in the production of material culture which highlights the importance of studying more specifically the differential impact that distinct modes of manufacture have on the end-product. While there is no empirical evidence to date that distinct 'modes of manufacture' differentially affect artefactual attributes in terms of copying error or 'mutation' rates, there are obviously numerous anecdotal statements that the mode of manufacture may play a role in generating physical effects and signatures in artefact end-products (Foster, 1960; Arnold and Nieves, 1992; Tite, 1999). In this respect, Orton et al. (1993, p. 124) mention that in wheel-throwing traditions the "mechanics of the pottery wheel dictate, to a certain extent, the forms of vessel that can be produced".

However, the mode of manufacture may also leave surface features in the clay (Courty and Roux, 1995; Lindahl and Pikirayi, 2010; Roux, 2010). Also, Foster (1960) adds to anecdotal suggestions in the archaeological literature that the mode of manufacture can be perceptually identifiable in metric attributes of pottery artefacts (Foster, 1960, p. 205).

Arnold (1991) also made the specific, yet anecdotal, observation that distinct levels of variation can be linked to different modes of manufacture. In recent decades, the study of variation has been addressed as a quantitative analytical method to assess metric differences in pottery assemblages (Arnold, 1991; Blackman et al., 1993; Kvamme et al., 1996). Arnold (1991) was concerned with the study of how 'standardisation' was generated in pottery assemblages and whether different forms of economic craft specialization varied in their level of standardisation. 'Standardisation' is defined by Arnold (1991) as a 'decrease in variation' in metric attributes between artefact assemblages. Thus, higher standardisation is associated with higher 'product homogeneity' (Arnold, 1991, p. 364; Blackman et al., 1993; Kvamme et al., 1996). Arnold's ethnoarchaeological study (1991, p. 364) primarily focused on how 'small-scale' ceramic producers in the case of rural Mexican potters generated levels of standardisation compared to intensive 'large-scale' producers of ceramic artefacts. Much to the contrary of the commonly held notion that hand formation techniques associated with small-scale production generate more variation compared to wheel-throwing techniques linked to large-scale production, Arnold's (1991) finding illustrated quite the opposite. Arnold's (1991) analysis of three communities that produced mall-scale Tuxtlas pottery in rural Mexico by means of 'hand formation techniques', showed that the hand-formation techniques generated lower measures of variation (measured by the coefficient of variation [CV]), compared to Roman cooking vessels produced by the 'wheel-throwing' technique. Thus, he drew the conclusion that the mode of manufacture may play a direct role in the generation of variation and that, consequently, "…Tuxtlas potters, therefore, generate a degree of product uniformity comparable to larger-scale, intensive potters" (Arnold, 1991, p.366). As a precautious note, however, it might be worth mentioning that no statistical assessment was applied to test the difference for statistical significance. In regards to the context of how manufacturing tools may affect variation, Arnold (1991, p. 367) mentions that tools applied in pottery manufacture may even potentially reduce variation, such that "morphological homogeneity may also result indirectly from the tools used during manufacture." In addition to the notion that equipment in the manufacture of material culture could directly impact artefactual attributes and may even affect patterns of variation directly (Arnold, 1991), determined efforts have been made to consider how distinct modes (i.e., 'techniques') of manufacture could possibly impact artefactual attributes. Arnold and Nieves (1992) illustrated that 'wheel-produced' bowls (also called "*cajetas*" produced by the Ticul population (Yukatan, Mexico) were significantly less variable compared with 'turntable-produced' bowls. However, these tool manufacturing traditions (wheel versus turntable) did generate significant differences in variation in the production of vessels, which led Arnold and Nieves (1992, p.108) to conclude that techniques utilising distinct tool traditions account for some variation between assemblages.

Arnold's (1991) idea that the mode of manufacture might play a role in reducing variation, and therefore increasing between-assemblage homogeneity, is very similar to a concept that Patten (2005, 2012) refers to as 'process controls'. According to Patten (2012, p. 26), process controls are defined as the "systematic impositions" that are implemented into the manual manufacturing process that lead to a reduction of unwanted variation. Therefore, process-control is the likeliness that the result of manufacture reflects the intention of the manufacturer and therefore enhances aspects of 'controllability'. In that respect, 'process controls' facilitate the reduction of undesired cultural mutations during the manufacturing process. Patten (2005, 2012) explains that process controls may be concepts or actions. However, process controls can also be the 'equipment' employed in manual manufacture (Patten, 2012, p. 30). In one anecdotal equipment-based example, Patten (2012) describes the use of a simple leather piece that can be used as a "soft anvil" during pressure flaking to counteract the impact of the pressure tool, since the leather piece facilitates the travel of the crack following the blow, such that longer flakes are produced.

These points again emphasise the idea that differences in 'input behaviour', in terms of manufacturing methods involving differences of equipment, could themselves ultimately be a target of cultural selection effecting long-term patterns of cultural change. That is, mutation rates (such as those frequently invoked in cultural evolutionary models) could, in principle, be directly influenced by even relatively subtle differences in equipment choices. If this is correct, this would indicate that patterns of material cultural change over the long term could be manipulated by cultural biases or other selective forces due to mutational variations induced at the proximate level by some relatively minor differences of equipment. In other words, even relatively small differences in manufacturing equipment may cause statistically significant differences in copy-error rates that will ultimately need to be given greater consideration in evolutionary approaches to material culture patterning. However, the question whether different tools, or subtle differences in experimental equipment, can differ in their ‘process control’ and can therefore differentially affect statistical patterns of variation in the attributes of manufactured cultural artefacts, has not (to date) been explored within an explicit experimental framework. Yet, Patten (2012, p.27) suggests that “properly conducted experiments exhaustively explore potential process controls by isolating variables”.

Given the foregoing considerations, the experiment described in this chapter was designed to test the effect of distinct modes of manufacture on artefactual attributes by using a controlled experimental framework and statistical analysis. An experimental context is optimal in that it facilitates direct consideration of whether even relatively subtle differences in two tools applied in the manufacture of material artefacts can, by themselves, generate distinct levels of shape variation and mutation, while other variables are held constant. Experiments are, therefore, useful tools to examine such factors of manufacture that are not directly observable in the ethnographic setting because “[e]xperimentation also identifies subtle controls that are not readily visible” (Patten, 2012, p. 28). As in previous chapters, the main focus is on studying variation in *shape* attributes of material cultural artefacts. There is increasing awareness that shape variation, not solely size variation as illustrated by evolutionary models employed by Kempe et al. (2012) and Eerkens and Lipo (2005), plays an important role in the evolution of material culture (Lycett and von Cramon-Taubadel, 2015). Shape may have specific functional and aesthetic importance in the archaeological record (Roche, 2005; Winter-Livneh et al., 2013), and may underlie evolutionary processes such as selection and drift mechanisms that determine spatio-temporal patterns. In this respect, the study was specifically focused on the investigation how subtle differences in two manufacturing tools utilized in the manual manufacture of experimental ‘handaxe replicas’, differently impacted shape copying error rates.

In this experiment, 60 participants were asked to each copy the shape of a model target foam ‘Acheulean handaxe’ from a standardised machine pre-cut foam block. The experimental conditions varied only by the ‘mode of manufacture’ that was applied to modify the foam block into the handaxe shape. In the ‘metallic peeler condition’, participants used a metallic vegetable peeler (Swiss peeler) to modify the foam block. In the ‘plastic knife condition’, participants applied a plastic knife to produce their foam handaxe replicas. The two modes of manufacture were chosen because both proved to be suitable and safe manufacturing tools which could be optimally applied to the floral plant foam blocks in the pilot research (see Chapter 2). Thus, these tools could be applied feasibly by novices in this copying task. In addition, the two tools also contained contrasting structural features and varied in the hand posture when holding them. The Swiss vegetable peeler referred to here as a ‘metallic peeler’ contained a blade that was placed between two ends of a fork such that the blade was perpendicular to the handle (Figure 6.1). The blade was movable at about 90 degrees. The mobility of the blade allowed for extra flexibility in moving the handle in a vertical up- and down motion without the blade detaching from the target object it was placed on. However, flakes of foam could be only removed, or ‘peeled off’, by pulling the blade over the foam towards the body. The flaking process therefore resulted in a back-and forth movement of the peeler. During the peeling motion, the hand position was vertical to the body. By contrast, the plastic knife’s blade was located sideways along the top part of the handle; the knife’s blade was also inflexible compared to the peeler’s blade. While the blade was moved over the foam in a back-and-forth movement in order to remove the foam (just like the peeler), the hand posture was horizontal to the body and therefore differed from that of the peeler. Unlike the peeler which could only remove foam in a ‘pulling’ motion, the plastic knife’s blade could remove foam by pulling and pushing the blade. Thus, despite the tool movements remaining largely equivalent (back-and-forth) the hand postures differed fundamentally between tools (vertical versus horizontal). In essence, the equipment was selected because it automatically instigated this difference in manufacturing ‘mechanics’ which may be operationally similar (at least conceptually) to some of those described earlier in the case of prehistoric production differences.

Of course, the experiment undertaken here was admittedly a simple one. However, in terms of the two key considerations described earlier—the methodological aspects (especially in terms of the wider programme of research instigated in this dissertation), and in terms of the wider potential implications that such considerations may have in terms of microevolutionary impacts on models of cultural change—even a relatively simple experiment may be justified at this point.

6.2 Methods and materials

6.2.1 Participants

60 participants were recruited at the University of Kent using the university's Job Shop and participated in the experiment in a laboratory facility in the School of Anthropology and Conservation. There were 30 participants female participants (mean age = 22, SD = 3.9, age range = 18-44) and 30 male participants (mean age = 23, SD = 3.8, age range = 18-34). Every participant was compensated with £4 for their time.

The data for one of the two experimental conditions (the 'plastic knife condition') stemmed from the participants recruited for the 20min time condition in Chapter 4 because the plastic knife condition contained the equivalent experimental set-up as the 20 minute time condition.

6.2.2 Materials

Standardised blocks of porous hard floral foam were used for the manufacture of the handaxe replicas (detailed description and foam block measurements are provided in Chapter 2). For foam manipulation, two different tools were used. One was a plastic knife (see Chapter 2) and the second device for foam manipulation was a Swiss potato and vegetable metal peeler (a type of peeler called 'REX Swiss Quality peeler'). As can be viewed in Figure 6.1, the metallic peeler contains two forks that elongate straight upwards from the handle and hold the partially movable blade horizontally in place (blade moves at about 90 degree freedom). Both the plastic knife and the metallic peeler were suited for left- and right-hand use. Dimensions for the metallic peeler and the plastic knife can be viewed in Chapter 2. Participants were provided with a lab coat to protect clothing from the foam dust as well as mouth protection and eye protection to guard from foam dust irritation. In addition, participants were provided with a countdown timer (participants were also reminded verbally of the remaining time left for task completion in regular time intervals).

6.2.3 Experimental conditions

In this experiment, the effects of the two contrasting foam manipulation tools on rates of shape copying error were tested in two separate experimental conditions. All other factors remaining equal, this meant that the only variable of manipulation was the type of manufacturing tool applied in the experimental task.

6.2.3.1 Condition 1 – The metallic peeler condition

In the 'metallic peeler condition', the effect of the metallic peeler device on the production of shape copying error was investigated. Here, participants applied the metallic peeler to the standardised foam blocks to produce the handaxe replicas.

6.2.3.2 Condition 2 – The plastic knife condition

In the experimental condition labelled here as 'plastic knife condition', participants used the plastic knife to manufacture handaxe replicas from standardised foam blocks.

Participants were distributed between the two conditions so that there was an equal number of n = 30 participants in each conditions. There were 15 females and 15 males in each condition. The equal numbers of males and females in each condition assured that sex differences were controlled for. In the metallic peeler condition, five participants (16.67% of participants in this condition) were left-handed and 25 participants (83.33% in this condition) were right-handed. In the plastic knife condition, three participants were left-handed (10% of participants in the condition) and 27 participants were right-handed (90% of participants in the condition). The distribution of left-handed and right-handed individuals fitted that of the population-level (Toth, 1985a; Corballis, 1989; Raymond et al., 1996).

All participants in this experiment were informed that the main task was to copy the *shape* of a target foam handaxe form as accurately as possible (details of the dimensions of the model target form can be viewed in Chapter 4, Figure 4.2). Specifically, participants were asked to pay attention to overall shape and form aspects but to prioritise copying the *shape* of the target form. Participants were provided with one minute to hold and view the foam handaxe target form from different angles. When the one-minute inspection time was completed, participants were placed at a table with a standardised foam block and one of the foam manipulation tools. Depending on the experimental condition, participants would either be provided with the metallic peeler or a plastic knife for the manual task. In both conditions, participants were additionally provided with a countdown timer (stating the remaining time left to complete the task). The target handaxe foam remained with the participants for the entire duration of the experimental task to control for memory effects. All participants were provided with a 20 minute timeframe to complete the copying task. During the experimental task, the experimenter informed the participants at five-minute intervals of the time remaining to complete the task.

If so required, all participants were allowed to wear spectacles and contact lenses so that confounding biases from major visual inconsistencies were controlled for. However, any external aids that could improve perceptual accuracy, such as scaled rules, were not permitted during the experiment. Participants were alternatively allocated to an experimental condition and took part only once in one of the two experimental conditions, without being provided with the possibility to repeat participation in the alternate condition. However, all participants in the pilot experiment completed the task within the time limit provided.

To increase the motivation of the participants, they were informed that a £20 book voucher was offered to the individual who most accurately copied the shape of the target form (i.e., the person who produced the least shape error rate). The voucher was offered additionally to the £4 reimbursement.

Once the complete set of handaxe replicas was obtained, the foam handaxe replicas were oriented according to a standardised orientation protocol as outlined in Chapter 2. In addition, all replicas underwent morphometric analysis and a set of measurements was obtained for 42 morphometric variables from all handaxes including the target form. These measurements were consequently size-adjusted to extrapolate shape-related data. Finally, shape copying error was calculated, as detailed in Chapter 3.

6.2.4 Statistical analysis

In order to determine whether the contrasting manufacturing tools generated distinct levels of shape copying error, a Mann-Whitney *U* test was applied at α = 0.05 to statistically compare the two experimental conditions (metallic peeler condition versus plastic knife condition). The more conservative Mann-Whitney *U* test was chosen since data regarding shape copying error was not normally distributed. The statistical comparison was conducted in IBM SPSS Statistics v20 and both the asymptotic p–value plus the Monte Carlo p-value (10,000 random assignments) were reported.

6.3 Results

When considering the rates of shape copying error in the two alternate tool groups, participants in the metallic peeler condition generated an average shape copying error rate of m = 0.121 (SD = 0.067). In the plastic knife condition, participants generated a mean shape copying error of m = 0.137 (SD = 0.047). The mean shape copy error rates for each of the 42 morphometric variables in each of the two experimental conditions can be viewed in Figures 6.1 and 6.2.

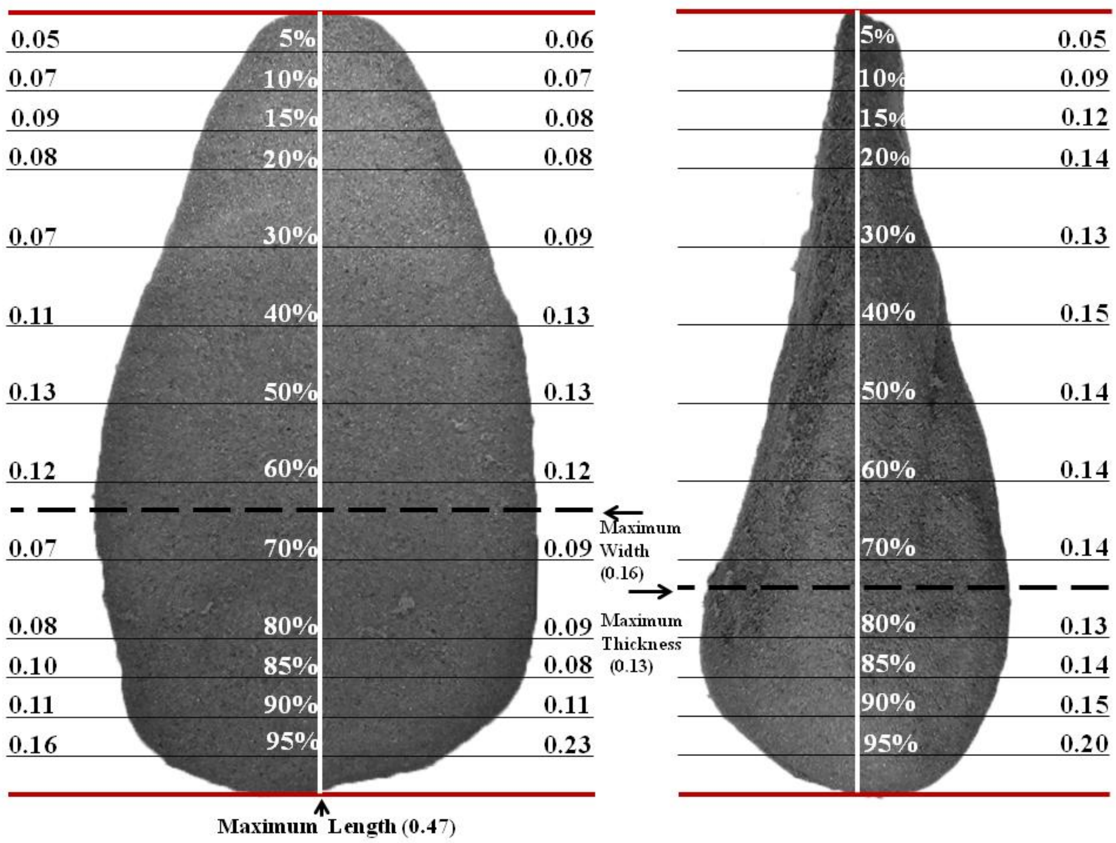

Figure 6.1: Mean shape error levels in the metallic peeler condition for each of the 42 morphometric variables.

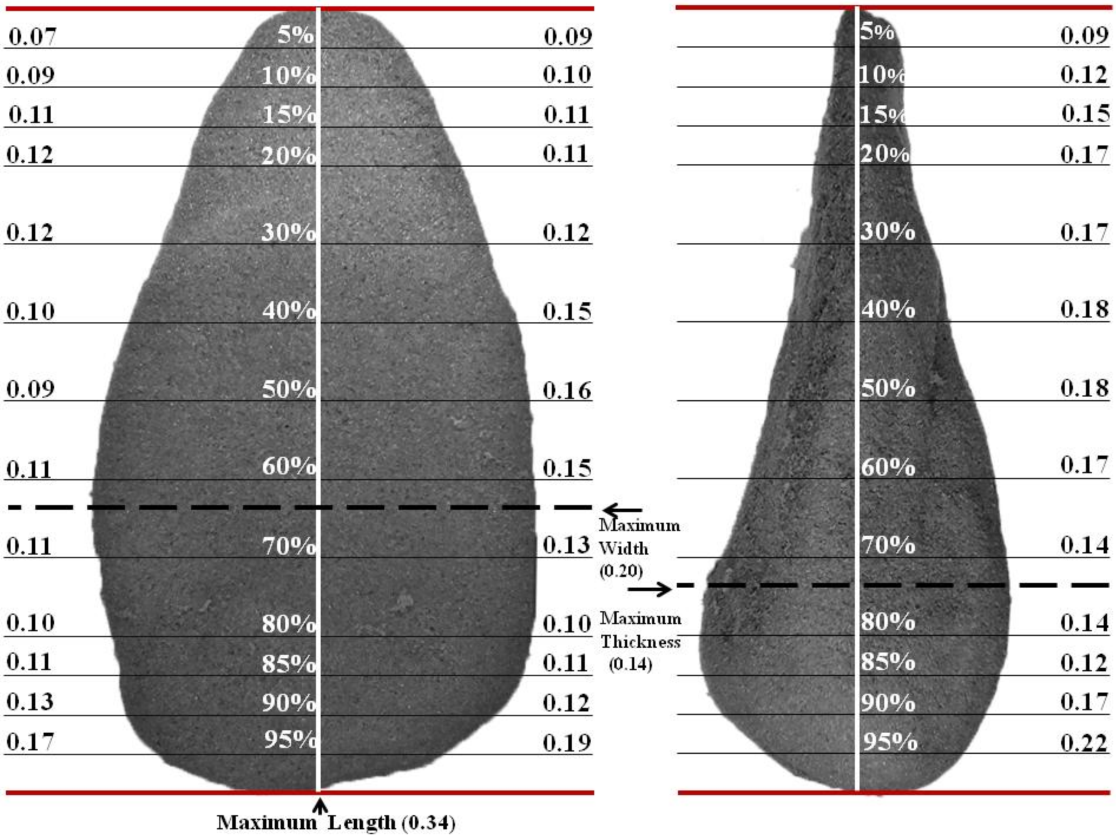

Figure 6.2: Mean shape error levels in the plastic knife condition for each of the 42 morphometric variables.

When statistically comparing shape copying error between the tool groups, the Mann-Whitney *U* test recorded a statistically significant difference in shape copying error ($n_1 = 42$, $n_2 = 42$, $U = 629.5$, asymptotic $p = 0.0234$, Monte Carlo $p = 0.0226$). The statistical assessment therefore provided evidence that participants generated a significantly lower rate of shape copying error when utilising the metallic peeler as opposed to the plastic knife.

Overall, these results show that subtle differences in the equipment applied to the manual manufacture of material artefacts can statistically affect patterns of shape variation, especially in terms of copying error or ‘mutation’ rate.

6.4 Discussion

Previous chapters of this thesis have discussed various conditions present in the manual manufacture of material cultural artefacts that can provide a source of distinct patterns of shape copying error. These studies have furthered recent experimental and computational endeavours (e.g., Eerkens and Lipo, 2005; Hamilton and Buchanan, 2009; Kempe et al., 2012), which highlight the relevance of studying copying errors as crucial sources of variation that affect material cultural evolution.

Here, in this experiment, it was investigated whether subtle differences in the equipment employed in the manual manufacturing task of three dimensional cultural artefacts could impact rates of shape copying error in statically distinct ways. The question whether differences in the equipment employed in manual manufacture, or in other words the 'mode of manufacture', generates patterns and trends in archaeological artefacts has been raised and addressed by archaeologists, although this has perhaps not been emphasized from an evolutionary standpoint in terms of the potential significance on 'mutation' rates. On the basis of experimental and ethnoarchaeological research in regards to stone knapping or pottery production, for example, it has been acknowledged that the mode of manufacture might generate distinct patterns, signatures and trends in the artefactual attributes (e.g., Foster, 1960; Arnold, 1991; Pelcin, 1997; Driscoll and García-Roja, 2014). In the example of pottery production, Arnold (1991) created the specific anecdotal association that distinct modes of manufacture, such as 'hand formation' techniques, as opposed to 'wheel-throwing' techniques could distinctively impact on the production of variation. While such assumptions have been rather anecdotal in regards to pottery production, determined advances have been proposed to experimentally investigate different impacts of hard hammer versus soft hammer percussion on specific flake attributes in reductive manufacturing traditions such as stone knapping (Pelcin, 1997; Driscoll and García-Roja, 2014). Specific examples of different 'modes of manufacture' have been investigated by researchers in ethnoarchaeological studies (Foster, 1960; Arnold, 1991) and within experimental contexts (e.g., Newcomer, 1971; Speth, 1975; Pelcin, 1997; Wenban-Smith, 1989; Driscoll and García-Roja, 2014).

The studies in this thesis are focused on manufacture-related factors and their effects on mutation rates in shape attributes in material artefacts. Hence, the question whether subtle differences in the equipment employed in the production of manually-produced artefacts are potential sources of copying error, merits further investigation in the wider context of these experiments. Since subtle changes to the equipment may confound or even alter experimental outcomes, the use of different modes of manufacture may also require investigation to better understand conditions required for consistency, or ‘replicability’, of experimental research of this kind. Perhaps more importantly, as a further means by which ‘mutation’ rate may be affected in the production of artefactual traditions, the issue has potentially important implications for modelling patterns of material culture change from an evolutionary standpoint. Specifically, manufacturing equipment may become the target of cultural biases (i.e., selective forces) directly as a result of the effect they have on differing rates of mutation that ultimately influence the fidelity potential of material culture traditions, and in turn, impact long-term trajectories of cultural change.

In the experimental task, participants copied a foam target form using a standardised foam block. The factor of manipulation in this experiment was the tools applied to shape the 3D Acheulean foam handaxes from the foam block. In the ‘metallic peeler’ condition, participants used a Swiss vegetable metal peeler to modify the foam. In the ‘plastic knife’ condition, participants used a plastic knife to create their foam handaxe replica from the foam block. The two different modes of manufacture differed in various structural properties and also in the manner how the hand was position when moving the tool’s blades over the foam. The statistical results showed that the plastic knife generated significantly higher shape error rates compared to the metallic peeler. This demonstrates that the mode of manufacture (in equipment terms) is a potent source of variation, mediated at the proximate level by distinct rate of copy error.

One of the important implications of this finding is that different traditions of equipment choice involved in production processes may represent distinct ‘process controls’ (*sensu* Patten, 2005). Process controls are factors put in place during the manual manufacture to increase the likeliness that artefactual end-products represent the intended outcome of the manufacturer. Process controls therefore reduce variation by “augmenting inherent skill” (Patten, 2012, p. 26) and are, according to Patten (2012), essential requirements for the existence and perpetuation of cultural variants. According to Patten (2012), equipment is one possible representation of process control. The findings of this study, whereupon the metallic peeler generated significantly less shape variation compared to the plastic knife, supports these intuitive, but anecdotal, assertions under controlled laboratory conditions. Described in precise terms, the metallic peeler affords a higher level of process control than the alternative mode of manufacture involving the plastic knife.

Importantly these results imply that different modes of manufacture representing distinct levels of process control directly impact the potential for ‘fidelity’ in the transmission of cultural variants. Equipment that represents different ‘process controls’ also varies in the potential for ‘fidelity transmission’ and therefore differently affects the cultural evolution of cultural variants. The characteristic of containing higher process controls also means that the metallic peeler contains an increased potential for higher ‘fidelity’ in the transmission of cultural variants. Conversely, the plastic knife, which generates much larger unintentional variation, represents lower process controls and contains a lower potential for transmission of given variants. Thus, a manufacturer is more likely to generate the desired outcome of a foam handaxe copy using a metallic peeler, as opposed to a plastic knife, at least within the context of this experimental task.

The finding of this experiment, illustrating that distinct tools represent distinct process controls, matter in respect to the archaeological record. This is because it was shown that subtle changes to the equipment applied to artefactual manufacture can generate physical effects in the end-product at distinct levels. Thus, traditions that represent distinct fidelity mechanisms differentially affect the promotion, or ‘preservation’, of cultural variants during the course of long-term cultural transmission. As Mesoudi et al. (2013, p.199) clarified, there must be “sufficient high fidelity such that technological knowledge, which is often cognitively opaque and difficult to acquire, is preserved and accumulated over successive generations”. While Mesoudi et al. (2013) were talking more in terms of the specific social learning mechanisms required for the long-term preservation of cultural variants (see also Chapter 5), the results of this experiment ultimately imply that tools with distinct process controls also contain statistically distinct potential for ‘fidelity transmission’ and therefore play an important role in the cultural evolution of material culture. A tool that represents high process control, and therefore promotes higher fidelity transmission, contains an increased prospective for the accurate copying of the morphometric shape attributes of material cultural artefacts at a high level of copying fidelity (i.e., hereditary continuity). Thus, equipment that contains high process controls increases the potential that detailed shape features manifestations are perpetuated over prolonged intergenerational exchange, generating more stable long-term cultural lineages.

The notion that distinct modes of manufacture can represent distinct levels of process control leads onto a further implication. Where shape ‘standardisation’ matters, or where high levels of process control are required to maintain specific functional or aesthetic cultural variants over the long-term, modes of manufacture that promote high levels of process controls and fidelity mechanisms may become ‘inherited’ by means of social learning by other members, as opposed to other traditions of manufacture. In other words, mode of manufacture that contain high levels of process control may become under the direct influence of selection, and spread in frequency in a population, where the high fidelity transmission of specific shape features in a material cultural artefact is essential, or advantageous. Ethnographic examples that specify how ‘modes of manufactures’ come under selection because of specific evolutionary advantages to the manufacturer have been observed by Roux (2010). In specific respect to pottery production in the region of the Southern Levant, Roux (2010) describes the social processes that led to the evolution of the mode of manufacture from the manual hand formation technique of ‘coiling’ to a new cultural variant called the ‘wheel-coiling’ technique. The wheel-coiling technique uses rotary kinetic energy of a wheel turning at “80 revolutions per minute” (Roux, 2010, p.221). As opposed to ‘wheel-throwing’ which is the use of the rotational centrifugal force in shaping the clay mass, the ‘wheel-coiling’ method is identified by using the centrifugal force of the turning wheel to shape and thin roles of clay that are placed on top of each other (Roux, 2010, p.219). Wheel-coiling eventually evolved further into the pottery production method of ‘wheel-throwing’. According to Shennan (2013), the fact that the ‘rotary kinetic energy’ mechanics of the wheel reduced the manufacturing time by 50% in the ‘wheel-coiling’ technique, compared to the manual tradition of the ‘coiling’ technique, is seen as a clear selective advantage to the manufacturer. Eventually, wheel-based pottery-manufacturing techniques became established and expanded in the Southern Levant as a result of this selective advantage, leading to wheel-coiling being adopted in the population.

Roux (2010) and Shennan (2013) describe the technological change and evolution of “mode of manufacture” in pottery production in respect to the selective advantage of the reduced production time. While Roux's (2010) example of pottery production in the Southern Levant is less concerned with how equipment impacts on artefactual attributes, it does highlight and describe a specific archaeological example of how traditions containing different modes of manufacture can be part of the cultural evolutionary process on the basis of selective mechanisms favouring features related to one tradition but not another, which leads to the expansion of the preferred manufacturing tradition via transmission networks (Shennan, 2013). Given the results of this chapter, a similar scenario may be proposed where low shape variation is desired or 'advantageous', utilising a mode of manufacture that ensures high process controls and high fidelity mechanisms would be selected over other manufacturing traditions containing equipment that represents lower levels of process controls. In fact, Patten (2012) has also stressed that process controls are themselves potentially 'heritable' and further elaborates that they are necessary, even required, for the perpetuation of cultural variants over the course of cultural transmission: "process controls are essential to the existence of recognizable patterns" (2012, p. 26). The results of the experiment reported in this chapter support this assertion, but also emphasize the role that manufacturing equipment itself has a mechanism of 'control'. In turn, the role of distinct patterns of manufacturing equipment—such as the introduction of 'soft' hammer techniques introduced at some point during the Palaeolithic—gain increased potency as a potential means of affecting the longer-term patterns of culture change to which the archaeological record bears witness, albeit mediated by their proximate role in influencing 'mutation' rates occurring at the level of the manufacture of individual artefacts.

A further important implication of this finding is that methodological control over specific variables, such as manufacturing tools that impact upon metric attributes in the study of artefactual variation, is of considerable relevance where evolutionary studies contain experimental application. Mesoudi (2011, p. 139) explicates that one of the greatest advantages of experimental application in the study of cultural evolutionary mechanisms is that a high level of control can be exerted such that some factors can be controlled whereas others particular factors of interest can be manipulated. In that respect, experiments allow for certain evolutionary historical events in material culture to be 're-run'. Lycett and Eren (2013) add that the utilization of experiments may be particularly valuable in the regards to the study of evolutionary mechanisms in the archaeological record, especially because of the advantage of the high ‘internal validity’ of experimental research as a result of the ‘precision’ resulting from the high level of control.

The results of this experimental study highlight that it is a fundamental requirement to control for differences in methodological aspects, such as equipment or manufacturing tools, where the study of factors impacting on unintentional mutation rates in cultural artefacts is at the core of experimental investigation (e.g., Gandon et al., 2014). This is because subtle differences in the equipment used in a context of similar nature to these experiments have been illustrated to make a substantial difference to the extent that rates of cultural mutations can underlie significant alterations. This finding illustrates that despite the advantage of producing accurate and precise data in a replicable contexts, it is of high importance to carefully consider any methodological inconsistencies that can potentially impact and ‘confound’ study results.

In sum, this experiment illustrated that defined differences in the equipment employed in manual manufacturing processes can distinctively impact rates of copying error. According to the study’s outcomes, delicate differences in the equipment employed can generate distinct patterns of shape error which may have specific implications for cultural evolutionary models. Firstly, within an empirical context that centres on the study of variation in material cultural artefacts, the experiment highlights the necessity for enhanced control and replicability within experimental investigations because differences in the equipment employed in artefactual manufacture can generate distinct levels of variation. In addition, since the concept of ‘process control’ is an essential process of manufacture that may underlie the long-term maintenance of cultural traditions, equipment that enhances ‘fidelity transmission’ through the greater capacity for process control may come under the effect of selective biases where traditions of shape standardisation matter in the long-term.

Chapter 7 - Discussion and conclusion

7.1 Short summary of PhD project

This PhD thesis represents a research project that was completed with the specific aim to further understanding of how new variation − i.e., cultural mutations − are generated by means of copying errors, which impact upon trends and patterns observed in the archaeological record. This endeavour has drawn on an experimental psychology approach, but was directed specifically toward material culture, while also taking advantage of a 'model organism' approach used in studies of biological evolution. It has also exploited morphometric approaches to variation, as used in both biological and archaeological studies.

In recent years, the concept that copying errors are a potent source of novel variation in cultural data has been explored in computer modelling research (Eerkens and Lipo, 2005; Hamilton and Buchanan, 2009; Kempe et al., 2012) but rarely within the specific experimental context (however, see Eerkens, 2000; Kempe et al., 2012, Gandon et al., 2013, 2014). Yet, these models elucidated that variation due to copying error is one of the evolutionary processes that can be measured in the metric attributes of material artefacts in the archaeological record. Apart from the feasibility of studying variation in cultural attributes, these models illustrated the implications that variation underlying drift (Neiman, 1995; Shennan and Wilkinson, 2001) and a variety of sorting mechanisms (e.g., Henrich and Boyd, 1998; Henrich and McElreath 2003) can have on patterns of artefactual change and diversification.

One of the major goals of the analyses undertaken here was to determine how copying errors, as sources of variation, become introduced during the manual manufacturing process. Using a unique experimental approach, where three-dimensional objects in the shape of Acheulean handaxes were used analogous to the 'model organism' approach applied in genetic research using *Drosophila melanogaster*, a range of experiments were conducted to better understand how rates of cultural mutations are generated in metric shape attributes during the manual manufacture of cultural artefacts. Thus, these experiments were based on the concept that when people produce cultural material artefacts, copy errors can be introduced as a result of a variety of factors that are specific to the context of manufacture. Some of the factors that were investigated here comprised economic and social factors, as well as differences in the traditions of manual manufacture. It was investigated whether varying the specifics of these components generated statistically distinct levels of copying error in the ‘end-state’ product of the assemblage in order to better understand how variation potentially enters the archaeological record during the manufacturing process.

7.2 Factors of manufacture generate distinct patterns of variation

At this stage, and taking these different studies together, it is appropriate to consider what knowledge was gained from the four different experimental investigations in terms of sources of shape variation in cultural artefactual attributes. It will also be considered how this knowledge informs the current literature that takes an interest in understanding factors that cause variation in artefactual attributes. In addition, at a later stage of this discussion, the methodological implications of utilising a ‘model organism’ approach to the study of variation in material culture are evaluated.

In a first experiment in Chapter 3, it was shown that cultural mutations in shape attributes are process dependent, such that irreversible (i.e., reductive-only) manufacturing traditions, typical for technologies derived from stone knapping, carry an inherently larger mutation load through random copying error compared to reversible manufacturing traditions like pottery or basketry. Therefore, stone tools, such as Acheulean handaxe tools, contain a fundamentally larger mutation load compared to reversible manufacturing processes (like pottery or basketry), since error during knapping processes are not easily reversed. This finding has particularly important implications for cultural evolutionary models, since it indicates that even artefacts produced under the same temporal, spatial and ecological circumstances, cannot be expected to generate the same levels of intrinsic (copy error) variation.

In Chapter 4, it was demonstrated that when increasing constraints are placed on artefactual production time, shape copying error rates change according to a ‘threshold’. When increasing constraints were placed on the production time of 3D Acheulean foam handaxes, mutation load increased markedly (in statistical terms) after a critical point was reached but not before. In that respect, economic factors like time constraints affect material artefact production and can lead to sudden increase in mutation loads if production is generated under sufficiently high time pressure. This finding that differential constraints placed on production time can substantially impact upon the load of mutations produced, has particularly important implications in respect to the evolution of material culture. This is because compared to other forms of culture, such as language, religion or behavioural norms and traditions (Mesoudi, 2011) material culture has the particular idiosyncrasy that a substantial amount of time investment in the production of every single material artefact item is a fundamental aspect of artefactual culture. Economic factors like time investment in artefact production therefore require particular consideration in respect to how variation is generated.

The experiment in Chapter 5 investigated the effects on shape copying error when imitative learning, which is associated with higher fidelity copying, was compared to emulation, which is linked to lower fidelity copying (Mesoudi et al., 2013). In this experiment, imitative learning significantly reduced mutation rates in metric shape error compared to emulation. These findings imply that in a population where the specific action sequences or manufacturing behaviours are learned that are essential to the production of a material cultural artefacts, cultural shape traditions have a higher potential to be sustainable in the long-term as opposed to a learning context where information is acquired from the end-state product alone. It is suggested that the prevalence of social learning mechanisms that contain higher copying fidelity might be essential in the maintenance of early cultural artefact traditions in hominin populations where shape preservation in artefacts mattered in the long-term.

In the last experiment of this thesis (described in Chapter 6), it was illustrated that even subtle differences in the equipment employed during manual manufacture can generate statistically significant patterns of metric variation in cultural attributes. More specifically, participants in the ‘metallic peeler’ condition generated significantly lower rates of shape-related mutations compared to participants in the ‘plastic knife’ condition. In that respect, the results highlight for the first time within an explicit experimental context the necessity for the instigation of ‘process controls’ as a key component for the perpetuation of long-term artefact traditions. The experiment also emphasizes the necessity for a controlled experimental context to the study of variation because tools used in manufacturing processes generate statistical effects in the metric rates of copying error.

Collectively, the experiments in this thesis draw an overarching picture that multiple micro-evolutionary factors involved in the manual manufacture of 3D cultural artefacts, such as the specific manufacturing tradition (Deetz, 1967), the tools utilized (Arnold, 1992; Arnold and Nieves, 1992) and time provided for tool manufacture (Torrence, 1983), can generate distinct statistical patterns of shape copying error. This has the predominant implication that the pervasive production of copying error introduced during the repeated manual production of material culture is a fundamental *process* which underlies selection and drift processes over the course of cultural transmission, ultimately leading to detectable change over the long-term (e.g., Eerkens and Lipo, 2005). Novel factual knowledge has been gained in the specific respect that manufacture-related dynamics affect mutation on metric shape attributes of cultural artefacts in the manual manufacturing process, even under conditions of high fidelity transmission through imitative social learning (Chapter 5). These results are analogous to findings in genetic replication processes of *Drosophila*, which illustrate that the production of copy errors in DNA basement strands in the form of mutations is an inevitable phenomenon (Maynard Smith, 1958). Thus, these studies make a fundamental contribution to the study of variation-generating mechanisms in material cultural evolution (Eerkens, 2005; Lipo and Eerkens, 2005; Gandon et al., 2014) by highlighting that the manual manufacture or production of artefact assemblages is itself a fundamental contributor to the continuous generation of cultural mutations. These studies add to recent knowledge gained from the literature which states that the production of cultural mutations in cultural artefacts is inevitable and a persistent occurrence as a result of motor, memory and perceptual limitations which generate detectable changes in the archaeological record over repeated cultural transmission (Eerkens, 2000; Kempe et al., 2012; Gandon et al., 2014). Variations of distinct factors that are associated with the manual production of cultural artefacts can generate distinct patterns of shape copying errors, which are of ultimate importance for the generation of cultural evolutionary models. Thus, variation generated from the manufacturing process potentially enters the archaeological record and underlies evolutionary transmission processes (cultural selection biases and stochastic drift) that determine spatio-temporal patterns of shape trends on the macro-scale level.

7.3 Cultural mutations and the concept of ‘evolvability’

This knowledge that there is a relationship between mutation rate in the metric characteristics of cultural artefacts, and patterns of change and variation resulting from factors directly related to the manufacturing process, has important implications for evolutionary models. Of particular note, these findings generate new insight in regards to the concept of ‘evolvability’. The notion of ‘evolvability’ is defined as the increased likelihood for material cultural traditions to change, adapt and diversify under the constant production of variation. Evolvability in the context of biology is described by Ridley (2004, p.587) as a mechanism which promotes evolutionary change:

> *“The term evolvability has been used to refer to how probable, or “easy,” it is that a species, or life form in general, will evolve into something new . Some species may be inherently more “evolvable” – more likely to evolve innovations and evolve into new , different species. Many suggestions have been made about factors that promote evolvability.”*

The constant generation of genetic mutations is one of the factors Ridley (2004) mentions in regards to the notion of ‘evolvability’ as the ultimate requirement for variation to persist. Fisher (1930, p. 21) specifically highlighted the importance of the continuous generation of mutations as an essential ingredient for the perpetual maintenance of levels of variation. Simpson (1953, p. 87) also regarded mutations as one of the ultimate drivers of evolution.

Resulting evolutionary change and diversification also occurs as a direct consequence of selection and drift mechanisms acting upon such new variation in artefactual attributes (e.g., O’Brien and Lyman, 2000; Shennan, 2002; Eerkens and Lipo, 2005, 2007). In some respect, therefore, the constant production of mutations throughout every transmission event as a result of imperfect copying facilitates the adaptability to change under shifting conditions (Maynard Smith, 1958). Therefore, cultural mutations are fundamental components for evolutionary change that underlie the evolutionary principle of ‘descent with modification’ in cultural lineages of archaeological artefacts (O’Brien et al., 2001; O’Brien and Lyman, 2003; Darwent and O’Brien, 2006). In addition, cultural mutations are essential requirements for cumulative cultural evolution (i.e., the incremental incorporation of effective innovations over time). The results produced in this thesis highlight the range of mechanisms inherent to archaeological artefact traditions that will have affected their ‘evolvability’.

Yet, at the same time, higher levels of mutation ‘loads’ associated with the increased potential for diversification can also be interpreted as the potential for ‘degradation’ of existing lineages (Morgan, 1932, p. 139). When applying the principle of evolvability to culture, the loss of cultural traditions is more probable when there is a higher level of random mutations. High mutation loads generate increased noise that inevitably weakens the phylogenetic signal in a cultural lineage. The concept of evolvability is, therefore, also associated with the likelihood of a tradition to go extinct in the absence of mechanisms that counteract such corruption of effective cultural traits. Simpson (1953, p. 87) mentions that heightened levels of genetic mutations can also decrease viability in biological populations. Similarly, Maynard Smith (1958, p. 111) adds that mutation-caused “change in a complex and well-adapted process of development is likely to disorganize that process”, and so is likely to cause a detrimental loss.

What can be learned about the notion of evolvability in material culture from the experimental findings in this thesis? Firstly, the studies in this thesis provided empirical verification that in a context where high mutation loads are generated in the manufacturing context, the ‘ease’ of a collapse of shape traditions would be particularly enhanced in the light of heightened mutation loads associated with the production process. The studies showed that high mutation loads can be generated, for example, where copy errors are not easily corrected as in the example of irreversible manufacturing traditions like stone knapping. In another example, it was shown that low fidelity manufacturing tools and low fidelity copying mechanisms like emulation source increased levels of copying error. The rapid disintegration of cultural artefact traditions through cultural mutations can also be further elaborated in the example regarding the increased ‘constraints’ placed on production time (Chapter 4). In Chapter 4, it was shown that copying errors produced under increasing constraints placed on production time can reach a threshold beyond which there is a sharp rise in mutation load. A rapid increase in mutation rates beyond the threshold would make artefact traditions highly unstable, potentially lowering the possibility for preferred cultural variants to be transmitted. Thus, manufacturing conditions placed under high time constraints ultimately face a higher potential for extinction, given the increased likelihood of high random mutation loads. This suggests that the implementation of mechanisms that effectively reduce mutation load, or shorten production time, would be required to enhance the likeliness for mutation loads to be kept below the task-specific ‘threshold’ in order to avoid cultural artefact traditions collapsing.

Chapter 3, which demonstrated that that high shape mutation loads are associated with reductive-only/irreversible manufacturing traditions, such as stone knapping, raises pertinent implications in this regard. Compared to ‘reversible’ manufacturing processes like basketry or pottery, the implications in terms of a concept of evolvability would be that the high mutation loads associated with irreversible manufacturing processes (such as stone knapping) are more readily disintegrated, because of the continuous disruption of the ‘heritable continuity’ (*sensu* O’Brien and Lyman, 2003) of artefact traditions with a specific shape morphology. O’Brien and Lyman (2003, p. 236) defined heritable continuity as the principle by which lineages of artefact traditions are passed on by means of cultural transmission. Some examples of stone technologies with specific shapes that resulted from irreversible (i.e., reductive-only) processes are the Acheulean, Levallois or projectile point technologies like Clovis and Folsom. Consequently, while cultural traditions manufactured from irreversible processes are in that respect ‘more evolvable’, these cultural artefact traditions have an increased potential for degradation and are less likely to be perpetuated over the course of continuous long-term phylogenetic lineages, compared to shape traditions resulting from reversible manufacturing processes.

Anecdotally, the principle of evolvability is highlighted in Figures 7.1 and 7.2, which illustrate the detrimental effects of the continuous production of shape mutations in Acheulean foam handaxes produced from reductive-only manufacturing traditions in 15 simulated ‘generations’. These figures visualise the plan- and profile-view of a cultural transmission chain where each member in the chain copied the shape of the end-state artefact from the previous chain member. Participants were provided with 20 minutes to complete the experimental task using a plastic knife and a standardised foam block. All participants in the two transmission chains (as depicted in Figures 7.1-7.4) were provided with the same instructions as those participants in the emulation condition (Chapter 5). Thus, handaxe shape was passed on via emulative learning. The only difference was that instead of being provided with the same model target form like in the social learning experiment in Chapter 5, participants in the transmission chains were provided with the previous member's foam replica as the target form; however, participants were not told that they were part of a cultural transmission chain. Only the first member in each of the two cultural transmission chains was provided with the original model target form that was also utilised in previous experiments in this thesis (labelled "starting model" in Figures 7.1-7.4). The figures illustrate 'descent with modification' within a laboratory context in the absence of natural, or cultural, selection processes. Without any biased sorting mechanisms in place (all shape attributes of the preceding model have equal fitness values) the original shape tradition is readily affected by drift because compounded copying errors gradually disintegrated metric shape features during the course of repeated cultural transmission events. In some respects, it could be argued that the 'shape degradation' due to the constant introduction of random neutral mutations (in the absence of biased cultural sorting mechanisms) represents an evolutionary 'default'. This is reminiscent of the utilisation of neutral drift processes as null models against which cultural selection mechanisms (social transmission biases like prestige or conformity) can be tested (e.g., Neiman, 1995; Bentley and Shennan, 2003; Bentley et al., 2004; Kohler et al., 2004; Mesoudi and Lycett, 2009; Shennan, 2011; Kempe et al., 2012; Kandler and Shennan, 2013). Here, it can be argued that the cultural transmission chain method generates an optimal experimental context where the effects of social biases can be tested against such 'null models' (i.e., random drift) within the laboratory. However, it should be emphasised that Figure 7.1 and 7.2 are illustrative of the general principles being argued here only; multiple repeats of such transmission chains, under controlled conditions, would be necessary for further more specific conclusions in this regard. Nevertheless, this also highlights further future lines of enquiry that could be followed as a direct outgrowth of the work undertaken here (see also below).

7.4 Factors counteracting mutation: imitation as an inheritance mechanism

Further findings in this thesis highlight for the first time that high copying fidelity mechanisms like imitation (Chapter 5) may be of particular importance in sufficiently reducing detrimentally high mutation loads in material culture traditions. The experiment in Chapter 5, which compared the effects of the contrasting social learning mechanisms of imitation and emulation, demonstrated that high fidelity copying mechanisms like imitation, in contrast to emulation, significantly reduced rates of shape copying errors. This finding may have relevant implications for material cultural traditions in specific respect to irreversible manufacturing traditions like stone knapping, which are associated with particularly high levels of mutation loads.

Specifically, when drawing together the combined findings from the experiments described in Chapters 3 and 5, it can be emphasized that high fidelity copying mechanisms like imitation may be required to sufficiently reduce high mutation loads associated with reductive stone tool traditions that contain a high level of shape standardisation. Therefore, stable archaeological patterns, such as those evident in the large spatial and temporal prevalence of the ‘Acheulean techno-complex’ may have required such mechanisms. Importantly, the Acheulean is associated with a recognizable change from simple flake tools, or cutting tools, that were not marked by the presence of a determined core form (Schick and Toth, 1993; Roche, 2005; Gowlett, 2006). By contrast, Acheulean bifaces contained a manufacturing process specifically targeted towards *shaping* the artefact itself (Roche, 2005; Lycett and Gowlett, 2008; Gowlett, 2011). Bifacial handaxes persisted for around one million years and first appeared in the archaeological record of Africa around 1.75-1.5 MYA (Lepre et al., 2011; Beyene et al., 2013). Therefore, these tool traditions testify to some of the longest-lasting preservations of shape in the archaeological record.

Here, therefore, the experimental study of the impact of social learning on variation in metric shape attributes has shed new light on the notion that the copying of details of the behaviours related to manufacturing technique in addition to the ‘end-state’ of artefact form − i.e., imitation (Heyes, 1994; Whiten et al., 2009b) − may have played an essential role in the long-term heritable continuity of the shape attributes in cultural artefact lineages. In that respect, the findings thus also support Morgan et al.’s (2015) recent experimental work suggesting that relatively complex social learning mechanisms (beyond stimulus enhancement and emulation) would have been required to initiate, but more importantly sustain, Acheulean traditions. In particular, the results highlight the importance of imitation in the maintenance of a tradition involving shaping. These findings therefore specifically inform about the role of social learning in the archaeological record and could be viewed as a directly addressing what Mithen (1999, p.389) describes as “limited reference…to the nature of social learning of premodern humans, as reconstructed from the fossil and archaeological records". This also supports research literature stating that "the reliance on social learning suggests that complex technologies, which are costly to invent, learn, and maintain, should be more dependent on social learning than simpler technologies" (Mesoudi and O'Brien, 2008a, p. 23; see also, Henrich, 2004). Imitation is often suggested to represent a prerequisite for cumulative cultural evolution (Boyd and Richerson, 1985; Tomasello et al., 1993; Tennie et al., 2009; Dean et al., 2012). In addition, the necessity for high fidelity transmission mechanisms, like imitation, to be present for the successful transmission of effective cultural variants in the face of cumulative copying error highlights a novel facet of evolution that is greatly underestimated in the current research literature. That is, that the longevity of cultural traditions depends largely on the *containment* of variation (i.e., mutation) via high fidelity transmission mechanisms.

The notion that high fidelity transmission can reduce random mutation loads raises the question that if evolvability is associated with the generation of mutation rates, what does it mean for cultural evolution if a substantial portion of variation is reduced during the inter-generational transmission of cultural artefacts? After all, the continuous production of mutations also generates the engine for evolution and adaptation to work on. The question can be approached based on the concept that high fidelity transmission of cultural traits through inheritance mechanisms like imitation allows for some of this variation generated in the manufacture of artefacts to be transmitted at higher replication accuracy. In the absence of mechanisms that reduce unwanted mutations, the persistence of effective cultural variants would be improbable. High fidelity copying mechanisms, such as imitation, could be understood as essential variation-reducing mechanisms even in the case of persistent imperfect cultural transmission and in the face of cumulative copying error (Eerkens and Lipo, 2005; Kempe et al., 2012). In that respect, 'replication' processes like imitation are somewhat analogous to DNA replication (e.g., Danchin et al., 2011). The DNA replication system ensures that 'copying errors' or genetic mutations that are introduced during the replication process are maximally reduced during a 'proof-reading' stage, which is carried out by repair enzymes (e.g., Maynard Smith and Sathmáry, 1999). Both the cultural and biological forms of replication systems need to ensure that favoured traits are passed on to subsequent generations at the highest achievable accuracy by keeping mutation rates low. To avoid excessive levels of mutation loads detrimental to cultural traditions, therefore, imitation allows for the sufficient reduction of continuously produced rates of mutation during inter-generational transmission to facilitate the accurate transmission of selected cultural traits. Thus, by illustrating the capacity of imitative learning to reducing random mutation loads that threaten to erode shape traditions during cultural transmission, it has been demonstrated for the first time exactly *how* imitation assures the long-term transmission of cultural traditions in the archaeological record. Despite the persistence of newly generated variation; it is not simply the case that imitation allows 'stuff' to be transmitted with greater ease culturally, but that it is a mutation-reducing 'repair' mechanism.

7.4.1 The concept of 'process controls' as a target of imitation

The finding that particular manufacturing behaviours can generate statistically distinct mutation loads, especially in irreversible processes such as stone tool knapping, leads to a further implication. In Chapter 6 it was demonstrated that specific components of the manufacturing process, like the 'equipment' employed during artefact production, can significantly reduce mutation loads. Ultimately, one of the implications generated from these findings is that factors of the manufacturing process that generate enhanced 'control' over sources of error would become apparent objectives for imitative learning. Patten (2005) labelled factors of enhanced control of the manufacturer over the artefact production as 'process controls'. In that respect, process controls are referred to as essential factors in the production process that assure that the end-state products of cultural artefacts consistently reflect the intentions of the manufacturer. It was illustrated for the first time in Chapter 6 that one form of process control is the 'equipment' employed during manufacture; both experimental populations were successful in copying 'handaxe' shape utilising distinct manufacturing tools, but copy error levels were statistically distinct. The notion that manufacturing tools can generate high fidelity transmission was shown on behalf of the metallic peeler which generated significantly lower rates of copying error compared to the plastic knife. The metallic peeler therefore represented the tool with higher process controls compared to the plastic knife.

The finding that certain manufacturing tools with higher process controls can substantially reduce patterns of variation, strengthens Patten's (2005) view of the necessity of such control mechanisms in the establishment of lasting cultural artefact traditions. Patten (2005, p. 64) urged that the utilisation of process controls can achieve almost “machine-like precision” in artefact end-state products (e.g., Martin, 2000). In that respect, Patten (2005) urges that in the absence of process controls, the iterated realisation of specific artefact types, such as ‘fluting’ of projectile points, which are the product of reductive processes, would not be possible and such technological lineages would fail to persist. The incorporation of process controls via imitative learning of specific tool use patterns during manufacture might therefore be a critical, often overlooked, aspect of manual manufacture which is essential for the production of artefacts. This would particularly apply to the accurate shaping of functional attributes, such as in the case of hunting equipment (e.g., Binford, 1978, 1979; Patten, 2005). Equally, process controls would also be required for the persistence of aesthetic attributes that may come under the influence of cultural selection, such as in the evolution of symbolic features that evolve to represent markers of group identification (McElreath et al., 2005; Efferson et al., 2008).

The importance of the concept of ‘process controls’ as a factor of error control is highlighted when comparing the cultural transmission chain produced by the plastic knife (Figures 7.1 and 7.2) versus the chain produced with the metallic peeler (Figures 7.3 and 7.4). The only difference between the two chains is that in Figures 7.1 and 7.2, participants copied the shape of the previous chain member’s foam handaxe shape using a plastic knife which is associated with lower level process controls (refer to findings from Chapter 6). Conversely, participants in the chain depicted in Figures 7.3 and 7.4 used the metallic peeler for the manufacture of their foam handaxe copy, with the metallic peeler being associated with higher level process controls. While statistical differences between the two chains were not verified for significance levels at this stage, it is at least obvious from anecdotal observation alone that the shape tradition from the original target model disintegrated at lower speed over the course of cultural transmission when the metallic peeler was used. Conversely, the original shape tradition disintegrated faster when the plastic knife is used. On one hand, the plastic knife generated visible signs of shape degradation by the third generation. On the other hand, the metallic peeler led to marked shape alterations only around the sixth generation. Thus, the reduction of random mutations by means of higher fidelity transmission on behalf of the metallic peeler led to the more long-lasting preservation of original shape components in the face of cumulative copying error. While this experimental simulation only anecdotally demonstrates the importance of the selection of process controls in manual manufacturing processes, it alludes to the possibility that such selection mechanisms underlying imitative learning of particular ‘techniques’ of manufacture are prevalent in the archaeological record and may play and unprecedented role.

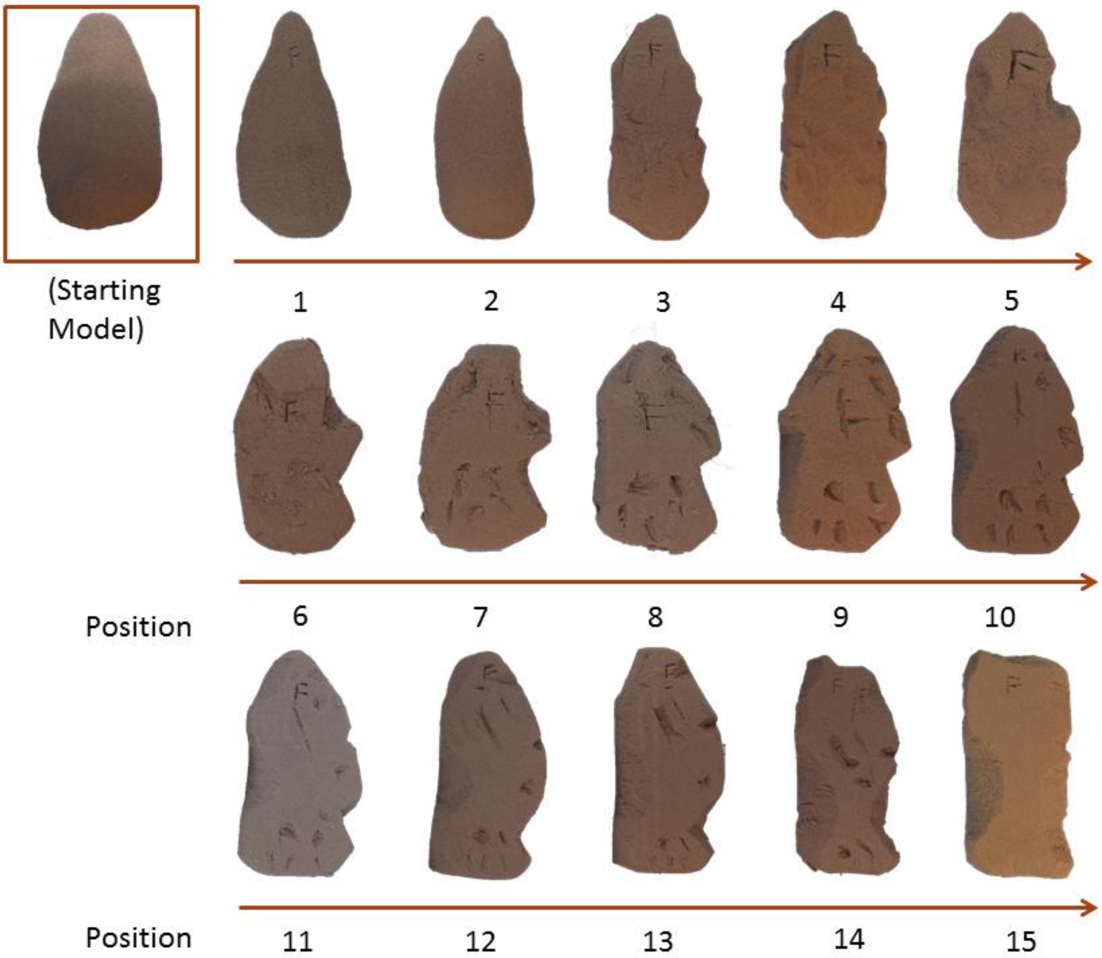

Figure 7.1: Transmission chain displaying the plan-view perspective of foam replicas produced with a plastic knife.

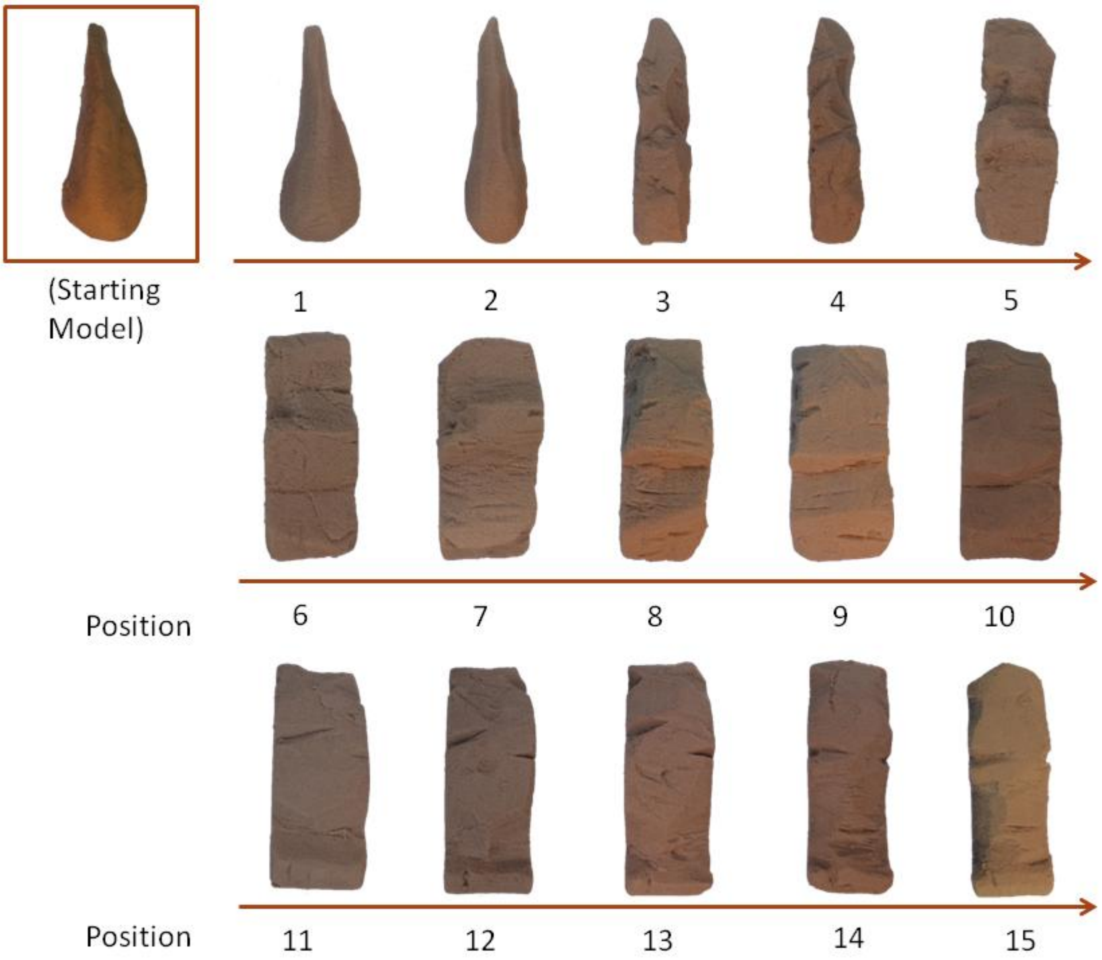

Figure 7.2: Transmission chain displaying the profile-view perspective of foam replicas produced with a plastic knife.

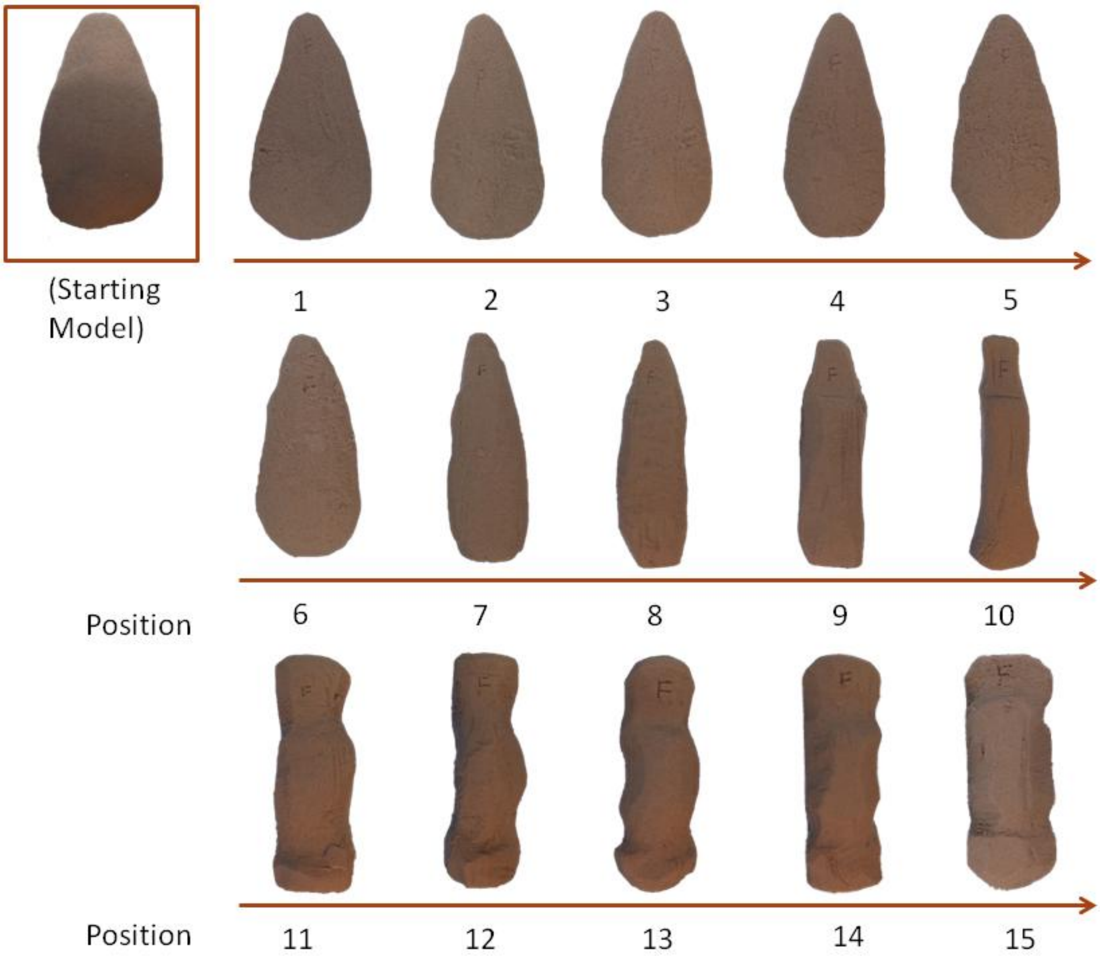

Figure 7.3: Transmission chain displaying the plan-view perspective of foam replicas produced with the metallic peeler.

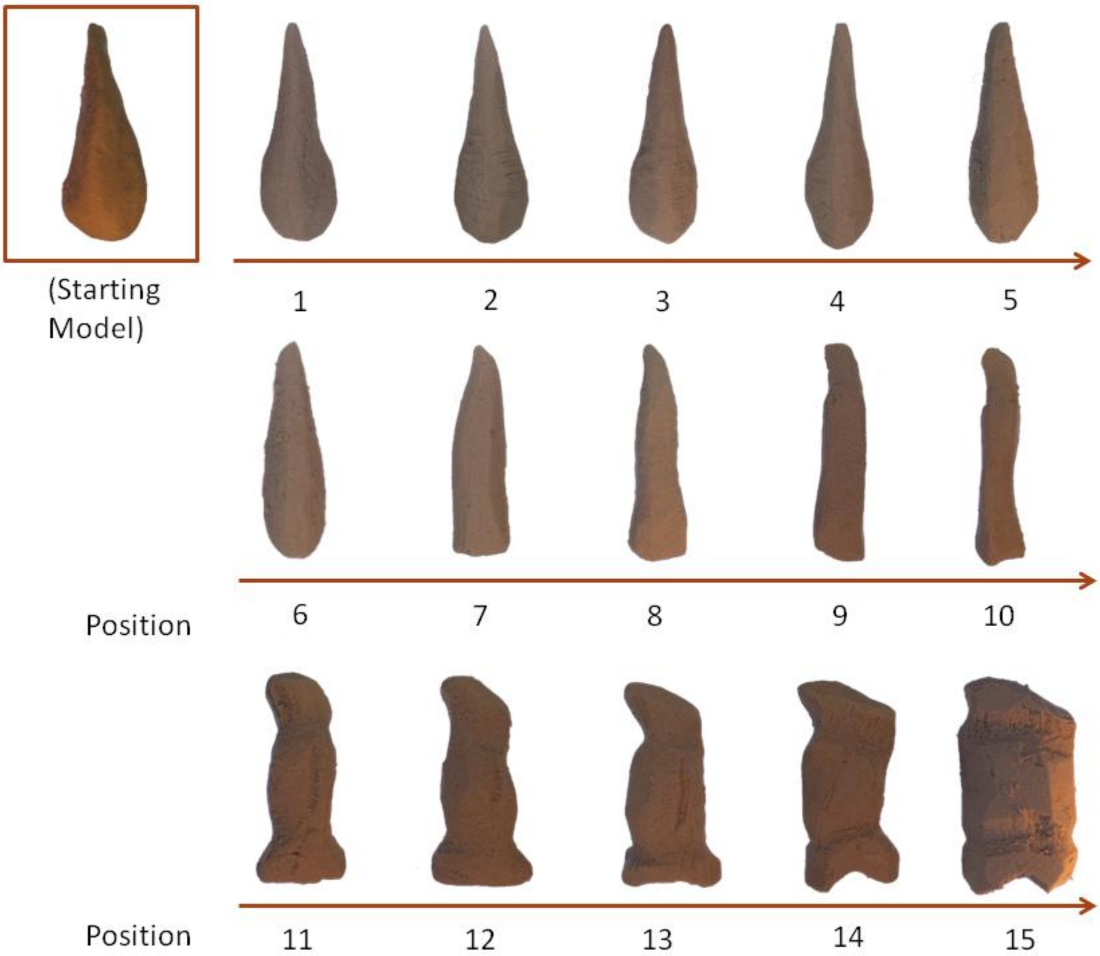

Figure 7.4: Transmission chain displaying the profile-view perspective of foam Acheulean handaxe replicas produced with the metallic peeler.

In that respect, it is shown for the first time that the imitation of successful manufacturing techniques (Chapter 5), and factors like manufacturing tools (Chapter 6) representing higher-level process controls are important requirements in the reduction of random mutation loads during the manual manufacture of real-world cultural artefacts. Fidelity transmission matters in terms of how patterns of variation are affected, thus where shape traditions matter over long-term, mechanisms of higher fidelity transmission may be relevant, which supports current research literature that stresses the importance of imitation in the long-term persistence of cultural traditions as an important factor for cumulative cultural evolution (Heyes, 1993; Tennie et al., 2009; Boyd et al., 2011; Mesoudi et al., 2013). In addition, the study of the effects of fidelity copying mechanisms in respect to irreversible manufacturing traditions, illustrated for the first time that shape traditions are therefore highly unstable in the absence of fidelity transmissions associated with imitation and high level process controls (as well as social biases that preferentially affect the transmission of effective cultural traits). More specifically, it was also described for the first time how culture evolutionary mechanisms on the basis of inheritance mechanisms such as imitation that effectively reduce mutation-loads, underlie the selection of enhanced ‘process control’.

7.4.2 Imitation underlying selection principles

In addition, one reason why imitation is seen as particularly relevant to cultural evolution is because it contains the capacity to incorporate behaviours that contain a specific selective advantage (Boyd et al., 2011; Shennan, 2013), such as those manufacturing techniques that enhance pattern control and, therefore, reduce unwanted mutations. As previously elaborated in Chapter 5, current research literature assumes that only high fidelity copying mechanisms like imitation contain the ability to incorporate novel advantageous modifications as one of the prerequisites for the ‘ratcheting’ effect underlying cumulative cultural evolution (Tomasello et al., 1993; Tennie et al., 2009; Boyd et al., 2011). The incorporation of advantageous innovations that can become incorporated into the archaeological record was previously described by Roux (2010) and further highlighted by Shennan (2013). Roux (2010) suggested an evolutionary transition from the manual ‘coiling method’ in pottery production to the ‘wheel-coiling’ technique since wheel-coiling was associated with a reduction in production time up to of 50%. The observation that pottery production for some shapes is faster using the rotational kinaesthetic energy of wheel-throwing methods, as opposed to purely manual means, has also been made by Arnold and Nieves (1992) in the Ticul population in Yucatan, Mexico.

Based on the findings of this particular research project, it has been demonstrated that imitation allows for the more accurate copying of such advantageous elements from the manufacturing process and may explain the incorporation and spread of innovative and economic manufacturing techniques that shorten manufacturing time because they actually reduce the likeliness that excessively high mutation loads are produced under tightened budgets on production time in such archaeological examples. Thus, as Shennan (2013) points out, such innovations may contain a selective advantage, one of such advantages would ultimately be the avoidance of ‘thresholds’ which are present under the influence of constraints acting on production time. It may therefore be emphasised that the incorporation of economic features leading to a reduction in production time would signify a clear advantage in respect to the long-term transmission of shape traditions.

7.4.3 The involvement of process control in craft specialisation

This newly gained knowledge on the effects of imitation and process controls as accurate replication processes also informs more specifically about the understanding of standardisation processes in cultural artefacts. Some cultural artefacts known to be standardised that are produced from reductive processes, include fluted points during the ‘Clovis’ or ‘Folsom’ periods of North America (Patten, 2005), or the strategic shaping of preferential Levallois flakes which depict higher standardisation relative to the flakes produced in order to generate these preferential Levallois flakes (e.g., Schlanger, 1996; Eren and Lycett, 2012) and the Acheulean techno-complex which contains more standardised shape preservation, compared to previous stone tool culture (Gowlett, 1984; Wynn, 2002; Petraglia et al., 2005). However, high fidelity learning like imitation and the selection of process controls also inform about the mechanisms necessary to achieve higher levels of standardisation in manufacturing processes such as ceramic production (Arnold, 1991; Arnold and Nieves, 1992). Arnold (1991) defines standardisation as the reduction in variation between artefacts in order to enhance between-artefact homogeneity (Arnold, 1991, p. 364; Blackman et al., 1993; Kvamme et al., 1996). It is further supposed that chronological changes that describe trends from less to more standardised assemblage production in the archaeological record was facilitated at least on “broad-scale” levels by the incremental incorporation of effective manufacturing techniques (Monnier and McNulty, 2010, p. 77). Enhanced standardisation in artefact assemblages is also conceptualised as an indirect key characteristic of craft specialisation (Arnold and Nieves, 1992; Costin, 2001; Roux, 2003; Kvamme et al., 2010). Craft specialization is defined as the dedication of few individuals (compared to consumers) to devote a larger amount of their time to acquire the necessary skills and expertise to be able to produce a specific craft (Costin, 1991; Arnold and Nieves, 1992; Roux, 2003).

Arnold and Nieves (1992, p. 94) also state that the relationship between standardisation processes and craft specialization may be explicated in terms of cultural evolutionary models. In that respect, one of the implications from these findings is that the incremental incorporation of process controls via imitative means (via cumulative cultural evolution or ‘ratcheting’) (Tomasello, 1999; Tennie et al., 2009) over the course of cultural transmission could explain the increasing complexity in manufacturing processes that would require specialised tool production. This is because the ‘learning’ involved to accurately produce standardised cultural artefacts can be so complex that the investment in the acquisition of knowledge related to complex manufacturing processes, that have accumulated sophisticated process controls over the course of cultural transmission, can become costly. Similar evolutionary processes have been noted to underlie the sciences which have been marked by the continuous accumulation of knowledge which generated the increased need for specialisation and branching of ‘expertise systems’ in recent decades (Mesoudi et al., 2013).

A particularly extreme example of such craft specialisation involved the century-long evolution of delicate swordsmith skills invested to produce the Japanese sword (Martin, 2000). The Japanese sword is an example of the cumulative incorporation of process controls in an effort to maximally “suppress variation” (Martin, 2000, p. 92). The Japanese sword was produced for the exceptional functional combination of seemingly incompatible attributes of hardness (associated with high sharpness) and toughness (i.e., high resistance against breakage in combat). In order to obtain the optimal combination of toughness plus hardness successfully, the production of the Japanese sword required the interaction of multi-step manufacturing processes including forging procedures, chemical procedures and extreme heat treatment. The complex manufacture was also otherwise highly failure-prone, costly and hazardous such that deviations through mutations were highly detrimental to the end-state product. Consequently, mutations were heavily selected against. This is similar to examples in biological evolution, where mutations introduced to organisms that are highly adapted to their environmental context can make the organism less adaptive (Morgan, 1932). In the case of the Japanese sword, the fact that even small rates of mutations were detrimental to its optimal functionality led to the conservative manufacturing process to become locked-in, leading to an evolutionary ‘stasis’ of the artefact components that defined the Japanese sword.

The rather extreme example of the Japanese sword highlights the importance of the implementation of process controls in the course of evolution for the establishment and long-term perpetuation of complex artefact production by actively counteracting unwanted rates of mutation loads during the manufacturing process. The example also emphasises the importance of understanding the interaction between evolutionary mechanisms and factors of the manufacturing processes to truly unravel how patterns of variation and change in cultural artefact products is generated. One of the important points this example highlights is the notion that how variation and change are created depends largely on factors and processes related to the manufacturing process. In addition, the insight from the research in this thesis that imitation can explain the incremental (i.e., cumulative) incorporation of process controls underlying standardisation processes, and potentially also craft specialisation processes, demonstrates the imperative requirement for increasing understanding of evolutionary processes affecting specifically patterns of variation generated during the production of artefactual culture, which according to the findings in this thesis appear to largely revolve around a notion of ‘error management’.

7.5 Evaluating the ‘model-organism’ approach in the study of variation and evolution of material culture

7.5.1 Advantages of the model organism approach

Here, the use of a model organism allowed for the discrete simulation of factors that affect evolutionary change in archaeological artefacts in the manual manufacturing process by enabling control over the manipulation of environmental, social and demographic factors. It can be argued in that respect that the model-organism approach complements current experimental research efforts in the study of evolutionary processes in the ethnographic record (e.g., Kameda and Nakanishi, 2002; Mesoudi and O’Brien, 2008a; Rendell et al., 2011; Derex et al., 2013).

Through use of a model-organism approach employed to simulate variation-generating processes in the archaeological record, progress was made to extrapolate knowledge on mutations as a process of variation. This is similar to the insights drawn on the impacts of genetic mutations in the biological sciences on the basis of laboratory-cultured model organisms like *Drosophila melanogaster* (e.g., Morgan, 1932; Dobzhansky, 1951; Greenspan, 2004). Thus, the experimental framework in this thesis lays a solid foundation for future evolutionary models to investigate more specifically identified factors that generate mutations during the manufacturing process of cultural artefacts.

More specifically, the studies in this thesis demonstrated that the study of 'tactile' features in manufacturing processes matters because manual production introduces statistical levels of mutation rates that can have dramatic consequences for the evolution of cultural variants. For example, it is emphasised that changes to manufacture-related factors such as constraints on production time and the use of different manufacturing tools can introduce statistical patterns of mutations that potentially generate substantial alterations to artefact traditions. In that respect, the 'model organism' approach also generated novel insights into the notion that physical properties specific to manufacturing traditions underlying artefact types like pottery or stone technology can have considerable effects on metric shape attributes. While it has been addressed by a multitude of studies on the basis of non-human and human animals that cultural variants (e.g., such as tool use) can be passed through mechanisms of social learning (Matthews et al., 2010; Mesoudi and O'Brien, 2008a; Horner and Whiten, 2006), the understanding that high-copying fidelity mechanisms are essential for cultural transmission of effective cultural variants because they actually 'suppress' high mutation loads during artefact production, that may be detrimental to shape traditions, has been uniquely highlighted within a secure context in the laboratory for the first time. It may therefore be emphasised that a model organism approach using 3D cultural artefacts is a successful endeavour as it complements other approaches to the study of cultural evolution like the 'virtual laboratory' (i.e., computer-based experiments) focused on the social transmission of cultural traits (Mesoudi and O'Brien, 2008a; Kempe et al., 2012; Derex et al., 2013). This is precisely because of the ability to identify, simulate and investigate representative physical or 'tactile' factors that underlie variation and change in the archaeological record in a fashion feasible only by experimental endeavours of the type adopted here.

Yet, even though computer simulation models are constrained in their ability to specifically investigate the effects of 'tactile features' of the manufacturing process of material culture, future synthesis of experiments of this nature together with computer simulation models can further build on this knowledge and investigate the impact of identified sources of mutation rates on cultural attributes produced during manual manufacture. Recent computer models have specifically combined insights from experimental data and simulations to investigate the effects of cultural mutations in artefactual attributes as a result of perceptual limitations (Eerkens and Lipo, 2005;

Hamilton and Buchanan, 2009; Kempe et al., 2012; Rorabaugh, 2014). In addition, the impact of mutation rates has also been incorporated in mathematical models that investigated more specifically the cultural transmission of discrete features (see Neiman, 1995; Shennan and Wilkinson, 2001, Kandler and Shennan, 2013). The general finding of this thesis that factors of manufacture, such as economic, social and mechanical components, generate wide-ranging patterns of variation, could be incorporated in future cultural evolutionary models that combine experimental, ethnographic and computational approaches (e.g., Bentley and Shennan, 2003; Kempe et al., 2012; Gandon et al., 2014). For instance, such models could expand their efforts to incorporate more specifically the impact of mutation rates derived from production processes of tactile features of artefacts over the course of repeated cultural transmission, in a fashion similar to other recent approaches on the study of copying error (e.g., Eerkens and Lipo, 2005; Hamilton and Buchanan, 2009; Kempe et al., 2012; Rorabaugh, 2014).

Specifically in this respect, the thesis has shown that in a context where little is understood about the manufacture-related factors on the generation of patterns of cultural mutations (i.e., as in the case of the archaeological record), a model-organism approach is essential for the simulation of cultural-evolutionary factors, which are relevant and can be feasibly investigated in the laboratory.

7.5.2 The advantage of experimental control in the study of variation

An example may be explored that illustrates the utility of a ‘model organism’ approach in respect to how it can inform innovative recent ethnographically-based research efforts, which follow similar goals of investigating the effects of mutation rates on cultural artefacts.

A recent study by Gandon et al. (2014) empirically illustrated that different cultures expressed culture-specific specific motor skills that differentially affected patterns of copying error (i.e., coefficient of variation) in metric attributes of pottery assemblages. In their study, expert potters produced 3D pottery artefacts in an experimental task where they were asked to copy four distinct model target shapes (i.e., target models were 2D images of the shapes of a bowl, sphere, vase or cylinder). The outcome of the experiment described homogeneity in metric mutation rates of morphological features within Indian and French sample populations but heterogeneity between distinct ethnic groups, illustrating that copy error rates were ‘culture-specific’. In addition, different cultures excelled (i.e., depicted lower error rates compared to other ethnic groups) at different pottery shapes, which was based on the assumption that rates of metric copying errors also depended on the ‘niche’ of learning within the culture-specific context (Gandon et al., 2014). According to Gandon et al. (2014, p. 105), the learning niche could be understood as the cultural convergence of a population on a subset of all possible motor skills available to accomplish a particular task because the task or result may be relevant to that population.

However, in the example of Gandon’s 2014 study, these experiments suffer a number of methodological inconsistencies specifically in regards to an issue of lack of control, which potentially confound the accuracy of their results. In this sense, the predominantly ethnographic context makes the understanding of the specific microevolutionary causes of variation difficult to determine. For example, the study by Gandon et al. (2014) did not take into consideration that different ethnic groups utilised different types of equipment during the wheel-throwing techniques employed. In Gandon et al.’s (2014) study, French potters used an electrical wheel-throwing technique, the Prajapati rotated the wheel using a long stick, and Multani potters used a ‘low-key inertia kick-wheel’ method.

Future research will, therefore, benefit from findings in Chapter 6, which specifically investigated the effects of differences in the manufacturing context on patterns of mutation rates. In one research experiment in this thesis in particular, it was illustrated that patterns of variation can be significantly discrepant based solely on differences in the equipment used to produce cultural artefacts. One of the important insights learned from the study in Chapter 6 was that control of equipment is a crucial necessity in empirical research efforts that are focused on the study of variation in manually manufactured cultural artefacts. Thus, based on these findings that even relatively subtle differences in tools can generate statistically different patterns of copying error, it is at this stage impossible to clearly discern from Gandon et al.’s (2014) research how much of the patterns of variation were driven by culture-specific differences in motor skills, or conversely, by mechanical differences in the tools utilised to produce the pottery shapes. Future research based on studying evolutionary mechanisms underlying patterns of variation in artefactual attributes would benefit from the high level of control exerted in the study of isolated microevolutionary processes, using a model-organism approach.

In addition, there was also heterogeneity in the learning context and demographic background of the three different cultural groups that could have influenced patterns of variation in motor skill. In Gandon et al.'s (2014) study, the sample population of French potters consisted of individuals who came from different regions of France where the individuals all learned at public schools. By contrast, the other two sample populations contained Indian potters, with each population derived from two different cultural backgrounds, which nonetheless came from the same region and learned within a more domestic context. It is, therefore, perhaps not surprising that French potters showed higher variability in their motor skills because of the potentially vast differences in the learning context, compared to the Indian potters.

Put together, these few points emphasise some of the overarching challenges that field-based studies face in achieving the enhanced control over a variety of confounding external factors (e.g., equipment and materials applied, learning context, demographic factors), compared to the experimental context. The experimental model implemented in the thesis emphasises that for the discovery of evolutionary mechanisms that describe trends and patterns of variation in the archaeological record (e.g., Darwent and O'Brien, 2006), careful control measures should be employed in empirical investigations to ensure that the interpretation of microevolutionary events and, importantly, the identification of the particular sources of variation during the manufacturing process, are determined appropriately.

7.5.3 Limitations of the experimental model-organism approach

While the strength of the experimental studies lies in its high level of internal validity, such as the invaluable advantage of studying the simulation of *isolated* microevolutionary factors that affect the generation of mutations (Mesoudi and O'Brien, 2009; Mesoudi, 2011), one of the major limitations of the experiments in this thesis is that resultant metric shape error copy rates from Acheulean foam handaxes are not *directly* transferable to levels of metric variation in archaeological artefacts. This is because foam handaxes are produced from raw resource materials unlike those of stone nodules to produce stone tool technologies. Laboratory-produced foam or plasticine artefacts naturally require the utilisation of distinct manufacturing techniques and tools in their production compared to real-world artefacts. Conversely, studies like that discussed by Gandon et al.' (2014) directly link to ethnographic research, which is a valuable contribution as it contains higher levels of external validity (*sensu* Mesoudi, 2011). Also, ethnographically-based findings may be more directly applicable or generalisable to 'real-world' conditions when compared to artificial cultures produced in the laboratory experiments. By contrast, findings from the empirical simulations in this thesis may be more limited in providing directly transferable patterns of shape error rates, at least to very specific archaeological contexts and material.

In addition, a further short-coming of the experiments in this thesis is that while they have made a demonstrable contribution to the understanding of the sources of factors that generate cultural mutations, the experiments are still limited in terms of the number of 'generations' involved. That is, little has been explored in terms how different factors related to the manufacturing context of artefact traditions over multiple transmission events. Research more specifically combining the production of copying error produced in the manufacturing process and multiple cultural transmission events would, therefore, complement other current investigations on the cultural transmission of microevolutionary processes (Eerkens and Lipo, 2005, 2007; Kempe et al., 2012). This is explored further below.

7.6 Contributions to future research

A case is made here for how future work can further incorporate methodological improvements by building on the strength of both the 'model organism' and the 'ethnographic' approach in the study of artefact variation.

One potential factor that models of cultural evolution could incorporate in future efforts is the production of real-world artefact types from the archaeological record in the laboratory context. Specifically, future research with particular focus on microevolutionary processes in cultural artefact evolution would benefit from empirical endeavours from the field of 'experimental archaeology', which is more specifically focused on the objective to understand mechanical, functional and procedural properties of artefact manufacture and implementation (Ascher, 1961; Newcomer, 1971; Jones, 1980; Courty and Roux, 1995; Driscoll and García-Rojas, 2014; Key and Lycett, 2014;

Wilkins et al., 2014). Ascher (1961, p. 793) defines experimental archaeology as the "operations in which matter is shaped, or matter is shaped and used, in a manner simulative of the past". Models of manual production, such as pottery manufacture, basketry and weaving which are still undertaken in different human cultures (e.g., Tehrani and Collard, 2002; Roux, 2010) and the re-enactment of past technologies, such as stone artefacts from the prehistoric past, have become focus of contemporary scientific research of factors underlying evolutionary processes in those specific artefacts (Prasciunas, 2007; Eren et al., 2014; Gandon et al., 2014; Wilkins et al., 2014; Lycett and von Cramon-Taubadel, 2015). Of course, attempts to understand impacts of manufacture-related factors on variation have been made in the context of experimental archaeology using flake and biface technologies from reductive stone knapping processes, for example (e.g., Newcomer, 1971; Prasciunas, 2007; Geribàs et al., 2010; Driscoll and García-Rojas, 2014; Eren et al., 2014). In another example, efforts have also been made in the context of experimental archaeology with respect to pottery production (e.g., Skibo, 1997; López Varela et al., 2002). Yet, the experimental investigation of the archaeological record in specific regards to cultural evolutionary models is still exceptionally rare (Mesoudi and O'Brien, 2008a; Mesoudi and O'Brien, 2009). This is despite the advantage that a stronger synthesis of cultural evolutionary models and the context of experimental archaeology would greatly enhance the understanding of specific evolutionary processes that guide variation and change in material culture during manual manufacture. Thus, the step from artificial material culture produced in the laboratory to the scientific investigation of real-world artefact production in the laboratory context would be a logical progression in the experimental investigation of evolutionary processes in the archaeological record.

One possibility that the future study of cultural evolutionary processes could realize, which would retain similarities to the experimental context in this thesis, is the instigation of simple real-world manual manufacturing processes that are easily acquirable by naive study participants, such that the study of population effects in material cultural evolution can still be achievable (e.g., Caldwell and Millen, 2008). In other words, some manufacturing processes, materials and cultural artefacts could be 'borrowed' from the ethnographic context. This can be achieved by implementing simple artefact production like the example of manual pottery manufacturing traditions known to be practiced by current human populations (Foster, 1960; Arnold, 1991;

Arnold and Nieves, 1992; Orton et al., 1993; Courty and Roux, 1995). Ethnographic studies have an elaborate catalogue that details the diversity of purely manual pottery production techniques, from simple hand-moulded pottery production which could be feasibly employed in the laboratory context (e.g., Foster, 1960; Arnold, 1991; Orton et al., 1993), like manual coiling techniques (Roux, 2010) and those utilizing simple tools (like marine shells) for the pottery shaping process (López Varela, 2002). The instigation of manual processes in the absence of mechanical aids like wheel-throwing techniques would be beneficial to capture the scale of human copying error introduced into metric components of the artefacts during the production process. Future experimental endeavours based on the study of microevolutionary processes that utilise production techniques with a realistic foundation in the ethnographic record would have the overarching benefit of producing results that can be more directly compared to data sets capturing macro-scale patterns observed in the archaeological record. In addition, this would facilitate the investigation of evolutionary simulation processes that more realistically capture aspects of ethnographic factors specific to manufacture (e.g., Geribàs et al., 2010; Gandon et al., 2013). Based on the findings in this thesis, such future research could attempt to replicate the findings from these experimental investigations in this PhD project to better understand how replications of these results relating to social learning, time constraints and equipment apply to parameters of real-world artefactual lineages. Importantly, the investigation of real-world artefact production techniques borrowed from contemporary or past artefact lineages would generate mutation rates more directly transferable to quantitative data obtained from archaeological artefacts. This is not a far-stretched idea. Recently, studies have compared levels of variation under the effect of biased and non-biased transmission processes derived from computer simulations with archaeological data sets (e.g., Neiman, 1995; Shennan and Wilkinson, 2001; Kohler et al., 2004; Hamilton and Buchanan, 2009; Kempe et al., 2012; Kendal and Shennan, 2013). Research on the basis of the instigation of real-world artefact production in the laboratory would, therefore, directly address the short-comings of the model-organism approach employed in this research project; yet still capture the advantage of investigating important physical and tactile components of the manufacturing process in a controlled manner.

The further introduction of the particulars and specifics of archaeological record into the laboratory to better understand and study microevolutionary processes would directly approach some of the limitations with ethnographically-based research (e.g., Gandon et al., 2013, 2014). Future experimental endeavours based on the study of microevolutionary processes that utilise production techniques with a realistic foundation in the ethnographic record (using manual production methods from pottery manufacture, for example) would have the overarching benefit of retaining its high level of control and 'internal validity'. Certain specifics of real-world artefact production could be incorporated into the experimental context (for example, similar to those in Gandon's (2013, 2014) studies). However, a controlled laboratory context would still exert higher homogeneity and control concerning factors such as, for example, the learning context (through teaching and learning trials of artificial traditions of 'motor patterns' in the population) and the equipment utilised for artefact production (e.g., Caldwell and Millen, 2009; Caldwell et al., 2012; Muthukrishna et al., 2013; Wasielewski, 2014).

7.6.1 Future synthesis of interdisciplinary methods to study cultural evolution in the laboratory

Future scientific approaches to the study of cultural evolution in respect to material culture would also benefit from the inclusion of additional interdisciplinary methods that are applied in the recent synthesis of cultural and biological sciences (Bentley et al., 2004; Mace and Holden, 2005; Mesoudi et al., 2006a; Mesoudi, 2007; Shennan, 2011; Lycett and von Cramon-Taubadel, 2015). Importantly, the model-organism approach can be expanded by introducing experimental models specific to the study of simulated cultural transmission from social and comparative psychology into the laboratory context. Such experimental models, like the 'cultural chain' method or 'group replacement' techniques, would allow the study of heritable continuity under the manipulation of factors that affect mutation rates (Jacobs and Campbell, 1961; Bartlett, 1932; Horner et al., 2006; Mesoudi, 2007; Schotter and Sopher, 2007; Caldwell and Millen, 2008; Mesoudi and Whiten, 2008; Kempe et al., 2012; Muthukrishna et al., 2013; Wasielewski, 2014). The intergenerational transmission of manufacturing techniques along cultural transmission chains, where variation in distinct factors such as manufacture tool traditions (e.g., Figures 7.1., 7.2) and social learning mechanisms can be traced, allows for the comparison of *temporal* patterning of variation in cultural artefacts over the course of a simulated time line in the laboratory context (e.g., Mesoudi, 2007; Caldwell et al., 2008; Muthukrishna et al., 2013; Wasielewski, 2014).

Further synthesis of cross-disciplinary methods that would facilitate an enhanced understanding of temporal patterns of variation over the course of cultural transmission can be achieved by incorporating methodologies such as phylogenetics from the study of biological evolution (O’Brien et al., 2001; O’Brien and Lyman, 2003; Mace and Holden, 2005; Gray et al., 2007; Jordan and Shennan, 2009; Lycett, 2009; Rogers et al., 2009; Tehrani, 2013). Phylogenetic models can investigate cultural transmission of artefact lineages in separate isolated groups, therefore, tracing such factors that affect evolvability of artefact traditions using phylogenetic signal as a measure of heritable continuity. Specifically, phylogenetic models would allow the study of the effects of copy error as a result of manipulations of the learning context or tool traditions in artefact lineages over the course of long-term transmission. Thus, if used in this manner, phylogenetic analyses have the power to test for the potency of particular microevolutionary processes along repeated transmission events even within a purely experimental context.

Phylogenetic methods are traditionally applied to investigate cultural transmission and diversification in artefact evolution and, therefore, are applicable to investigate population-level effects (O’Brien et al., 2001; Darwent and O’Brien, 2005; Mace and Holden, 2005; Buckley, 2012). A unique combination of experimental models of cultural transmission coupled with cladistics analysis from biological sciences would, however, generate a framework that could bridge the micro- and macroevolutionary patterning of variation, while also allowing the tracing of trait evolution during controlled and observable transmission events. One simple example of investigation that would directly build on findings in this thesis would be the examination whether high copying fidelity learning (i.e., imitation and teaching) would generate higher phylogenetic signals, compared to lower copying fidelity learning (emulation) over the course of repeated cultural transmission (i.e., utilising cultural chain methodologies). Such future frameworks have the power to test specific assumptions related to, for example, how the suppression of mutation loads through high copying fidelity mechanisms like imitation and teaching affect variation in the long-term, using interdisciplinary methods specialized for the study of evolution. In addition, such efforts would build on the findings in this thesis regarding the factors relevant for the continuity of technologies derived from irreversible manufacturing processes that underlie shape traditions like the Acheulean. Thus, testing such mechanisms of high fidelity transmission statistically using cultural transmission methods plus cladistics methods would be particularly useful for the further understanding of the factors underlying the long-term persistence of artefactual traditions in the archaeological record.

More can also be done to investigate the evolution of manufacturing techniques and the instigation of ‘process controls’ that could have played a role in past behaviours underlying complex stone tool technologies. Future experimental research could investigate the inter-related factors related to the accumulation (‘ratcheting’) of effective process controls in complex manufacturing processes on the basis of high fidelity learning mechanisms, such as imitation or teaching. Such endeavour would set foot in the direction of understanding the fundamental principles underlying tool specialisation and standardisation processes that are employed to maximally reduce unintended variation (Costin, 1999; Arnold and Nieves, 1992; Martin, 2000; Patten, 2005). Future research could achieve this by generating data sets that are comparable to those produced in this thesis by combining and manipulating different factors known to affect variation, like the social learning context plus the equipment, within one experimental context. Specific assumptions could be tested in regards to the question whether ‘combined’ effects of high copying learning, like imitation, and tools that represent higher-level process controls (i.e., metallic peeler for the production of foam handaxes) could further reduce mutation rates compared to those obtained from experiments in this thesis that investigated such factors in isolation. This would deepen the argument regarding the specific individual-level factors required to generate the ‘heritable continuity’ underlying long-lasting shape traditions in the prehistoric past and further enhance the understanding regarding the prerequisites for cumulative cultural evolution.

It may also be noted that the ‘model organism’ approach developed here, may be extended to investigate the transmission of functional variability. The experiments in this thesis were specifically focussed on investigating the transmission of shape variation, where traits were considered equal in terms of their selective status. However, this experimental model could be modified to also accommodate the scientific study of, for example, biased sorting mechanisms that affect functional attributes, in order to further our understanding how functional traits were passed on in the archaeological record (see, for example, Rogers and Ehrlich, 2007; Shennan, 2008b). Moreover, future research could additionally focus on the specific factors that may affect the transmission of decorative motifs, which were functional for symbolic signalling purposes (e.g., Efferson et al., 2009). A laboratory approach of the type described in this thesis could certainly be modified and extended in order to study such phenomena, including also a more extensive investigation of complex social learning mechanisms. An example could be the investigation of the effects of teaching and language on shape variation, compared to purely observational learning. In addition, this experimental model would also be suitable for the investigation of whether different handaxe areas exhibit different levels of variation that might have differing functional utility in the context of their use as tools. In that respect, shape variation may affect some morphological features differently from others, which would certainly contain interesting implications for the evolution of shape traditions.

7.7 The study of cultural evolution: is it the study of cultural transmission or the study of copying error?

While recent decades are marked by the rapid expansion of the meticulous framework of synthesised methodologies and theories aimed to understand how cultural *transmission* structures variation in the archaeological record (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985; Eerkens and Lipo, 2007; Whiten et al., 2009a; Mesoudi, 2011; Lewis and Laland, 2012), the overarching contributions of the research collected in this thesis lies in the notion that variation produced during the manufacturing process is affected by cultural mutation rates that arise from imperfect copying.

The notion that ‘imperfect copying’ exists and might impact patterns of trends and change over time has been highlighted by previous studies in respect to sources of variation associated with limitation of human perceptual (Eerkens and Lipo, 2005), memory (Eerkens, 2000; Eerkens and Lipo, 2005) and motor skills (Gandon et al., 2013, 3014). Other studies have been concerned with how evolutionary mechanisms structure such variation on behalf of drift and selection processes in the archaeological record (e.g., Neiman, 1995; Shennan and Wilkinson, 2001). In addition, phylogenetic approaches describe such patterning of variation on the basis of the structuring artefact lineages according to what has also been conceptualised as “shared mutations” that are passed on via cultural transmission, for example (Shennan, 2008a, p. 80; O’Brien and

Lyman, 2003). However, the systematic investigation of the production of unintended random copying error has been conducted in this thesis for the first time in specific respect to the manufacturing context of material cultural artefacts. The thesis illustrated that the manipulation of a variety of factors related to artefact manufacture, as well as social and economic aspects, all generate distinct statistical patterns of shape copying error in artefactual end-state products. These findings provide insights regarding the role that the manual manufacture of cultural artefacts plays in sourcing patterns of copying error. The thesis emphasises the importance of unravelling the microevolutionary factors that cause spatial and temporal patterns of variation underlying "descent with modification" in lineages of cultural artefacts (Bettinger and Eerkens, 1999; Mesoudi, 2007; Mesoudi and O'Brien, 2008a; Shennan, 2011).

More specifically, the thesis has illustrated that despite the ability of high fidelity transmission mechanisms such as imitation, and use of more effective tools (such as the metallic vegetable peeler in the context of plant foam removal) to substantially reduce unwanted mutation loads, the generation of copy error in metric shape in 3D attributes analysed in the manufacturing process remains an inevitable and pervasive phenomenon in the production processes of cultural artefacts. In that respect, the findings in this thesis generate statistical data empirically verifying what Basalla (1988, p.103) referred to as "failure of replication". Specifically, Basalla (1988, p.103) states that "no matter how dedicated a copyist is faithfully duplicating an original, the copy always differs from its model. This is true even when the copyist and the original maker are one and the same person; the mindset, materials, tools, and working conditions are all slightly different and that makes exact reproduction impossible." The thesis confirmed the notion of imperfect copying as a pervasive phenomenon underlying transmission events. Yet, it was also shown for the first time that delicate differences introduced in the production process generates statistically distinct patterns of variation. Thus, if even slight differences in the manufacturing process of similar artefact types become established in distinct populations, such delicate variations in the manufacturing process potentially become manifested in patterns of variations detectible in artefact traditions between populations (e.g., Eerkens and Lipo, 1999).

The necessity of high fidelity copying mechanisms like the imitation of high level process controls, highlighted by this work as key components required for the heritable continuity in the archaeological record, emphasises that the study of cultural transmission in the archaeological record could be conceptualised as the study of '*management of error'*. Moreover, the long-term persistence of standardised shape traditions in irreversible manufacturing processes describing early stone tool technology like the Acheulean would not be possible without the implementation of variation-counteractive mechanisms, such as high-fidelity social learning and high-level process controls, in the face of high mutation loads threatening the degradation of shape traditions. An extreme example being the standardisation achieved in the Japanese sword which illustrates the level of expertise, labour and complexity regarding the manufacturing process required to maximally reduce the pervasive production of random new variation underlying every production event (Martin, 2000).

Thus, one of the predominant theoretical insights gained in this research project is that these studies emphasize that the theory of cultural evolution can be somewhat re-conceptualised in regards to material culture. Theories of cultural evolution are commonly defined through the study of cultural *transmission* of artefactual attributes via social learning as an inheritance mechanism that structures variation across evolutionary trajectories (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985; Eerkens and Lipo, 1999; Mesoudi and O'Brien, 2008a; Mesoudi, 2011). A great body of work has conceptualised how variation is passed on through social learning (Whiten et al., 2009b), transmission biases (Henrich and Boyd, 1998; Eerkens and Lipo, 1999; Henrich and Gil-White, 2001; Mesoudi and O'Brien, 2008a), drift (Neiman, 1995; Shennan and Wilkinson, 2001) on the basis of cultural transmission (O'Brien et al., 2001). As Cochrane confirms (2009, p. 114), variation in the archaeological record is largely explicable on the basis of "cultural transmission and related evolutionary processes".

However, this thesis has demonstrated that cultural evolution is not just about the study of cultural transmission *per se*, but about the study of the production of variation as a result of 'imperfect replication'. Hence, inherently, cultural evolution itself is about the *management* of the prevalent instigation of copy error during repeated cultural transmission processes, such that cultural traditions can persist in the long-term. The study and understanding of variation-generating mechanisms was largely based on an experimental investigation on the microevolutionary level, which ultimately underlies processes acting on the level of macroevolutionary patterns such as those observed in projectile points (O'Brien and Lyman, 2003) or in Acheulean shape variation (Lycett and Gowlett, 2008) as well as ceramic designs (e.g., Neiman, 1995; Kandler and Shennan, 2013). The studies in this thesis demonstrated how the understanding of macro-scale level processes of variation and change (e.g., Bettinger and Eerkens, 1999) can be achieved on the basis of the study of mutations generated in the manufacturing process of laboratory 'artefacts'.

It is emphasised that to further understand macroscale patterns of variation in the archaeological record, future research should expand on the controlled investigation of the microevolutionary processes utilising specialised models that can trace the transmission of copying error between individual transmission events. On the basis of the model-organism approach it was shown for the first time that manufacture-related factors like social learning mechanisms, components of the manufacturing tradition and equipment employed, as well as economic facets of the time investment are all factors affecting the generation of rates copying error. The experimental study of cultural mutations can provide important insights into the factors that affect micro-evolutionary patterns, which ultimately affect spatial and temporal change and variation on the macroscale level.

7.8 Conclusion

The Darwinian evolutionary framework has been adopted to study the cultural transmission processes that shape patterns of variation and evolutionary change and that describe 'descent with modification' in lineages of material cultural artefacts (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985; Mesoudi et al., 2004, 2006a; Cochrane, 2009; Shennan, 2008a; Shennan, 2011; Lycett and von Cramon-Taubadel, 2015). As part of this PhD thesis, the question of how microevolutionary modifications come to explain population-level trends in the archaeological record during the manufacturing process has been addressed utilising a novel interdisciplinary experimental model (Eerkens and Lipo, 2005; Mesoudi and O'Brien, 2008a; Coward, 2008; Gowlett, 2010). This thesis proposed an investigation on the basis of simple experiments that explored the effects of a variety of manufacture-related components on metric shape copying error in 3D cultural artefacts produced in the laboratory utilising a 'model-organism' approach adopted from the biological sciences (e.g., Morgan, 1932).

Taken these experiments together, this scientific approach demonstrated that the manufacturing process matters for the study of variation because it plays a vital role in the production of cultural mutations in metric shape attributes of cultural artefacts. In that respect, the thesis showed that contrasting manufacturing traditions such as irreversible processes underlying stone knapping and reversible processes found in the manufacture of pottery, for example, generated rates of shape copying error that were significantly different. Other factors that were demonstrated to source cultural mutation rates at statistically significant levels were the equipment employed during production, economic factors like constraints placed on production time and the types of social learning underlying cultural transmission.

In specific respect to the archaeological record, these studies highlighted that the multivariate 3D metric shape attributes are continuously affected by the ‘failure of replication’ that affect every repeated cultural transmission event. This effect is particularly relevant for irreversible manufacturing traditions involved in the production of long-term stone tool artefact traditions like those known in the Acheulean, since irreversible manufacturing processes contain inherently larger mutation loads. However, it was further shown that the long-term persistence of cultural traditions depends on the incorporation of mutation-counteractive mechanisms as part of the ‘replication process’ to facilitate the passing of effective modifications in the long-term as part of a process that underlies heritable continuity. Therefore, the long-term perpetuation of cultural variants (also a fundamental requirement for cumulative cultural evolution) requires the instigation of mechanisms of high fidelity transmission that considerably reduce the detrimental effect of high mutation loads.

The presence of high copying fidelity mechanisms, like imitation, may have been relevant in hominin lineages that produced stone technology with determined shape properties, like the Acheulean, because irreversible manufacturing traditions are particularly prone to shape disintegration in the long-term. In addition, it has been shown for the first time in specific respect to material artefact production that long-term traditions of cultural artefacts require the instigation of manufacturing tools representing higher-level ‘process controls’ that can significantly reduce cultural mutation rates. As such, this thesis successfully combined experimental models from psychology and morphometric analyses for metric shape quantification adopted from biological and archaeological sciences (Lycett, 2007b; Costa, 2010; Chauhan, 2010) to better understand how variation shapes the archaeological record. These studies provided multiple findings that allude to the overarching theoretical implication that the study of cultural evolution is not only about the study of the transmission of cultural attributes, but equally about the investigation of the ‘failure of perfect replication’. Consequently, it is also about study of the processes and factors that underlie the *management* of copy error that affects every cultural transmission event, and potentially affects the macroscale patterning of variation and change in seen in artefact lineages.

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Appendices

Appendix A - Sample instruction sheet (Chapter 4)

A1) Instruction sheet for the 20minute time condition

Please read the following information carefully before you decide to take part; it will give you relevant information about what you will be asked to do. If you decide to take part after reading the instructions, please sign the attached form to say that you agree. You are still free to withdraw at any time and without giving a reason or losing your right for the compensation of £4. Also, please do take the opportunity to ask if you have any questions regarding the experiment, I am happy to answer them. I will also provide you with a debrief sheet at the end of the experiment. It will inform you about my study goals and the research background of this study.

You will be shown a foam model of a stone tool called a ‘handaxe’. In this experiment you will be asked to replicate the shape of the model handaxe with a tool and a block of material that I will give you shortly. Your aim in this experiment is to copy the model handaxe in front of you **as accurately as you can**. Copying the SHAPE is important than the size, so please bear that in mind.
You will be given one minute to examine the model handaxe and then you will have 20min to make your replica. To begin with please inspect the handaxe model in front of you from all sides and take into consideration its overall form and, in particular, *shape*.
After the first minute I will let you know that you may start and I will provide you with a block of foam and a plastic kitchen knife from which you will make the handaxe replica. The model handaxe will be with you throughout the experiment for further reference. You may compare your handaxe replicate with the model handaxe at any time but you must not put the model handaxe on the block of foam and trace it.
I will video-tape the process of the handaxe making, however, the camera will focus on your hands only; your face will not be recorded.
The person whose replica handaxe is closest to that of the model handaxe will win a £20 Amazon voucher!

If you agree to participate please read the consent form carefully and sign it.

Appendix B - Intra-rater reliability test for the video coding system from the social learning experiments

B1) Intra-rater reliability test results from 10 random videos in the imitation condition

Videos	*Codes	**IM 12**	**IM 25**	**IM 15**	**IM 29**	**IM 2**	**IM 18**	**IM 19**	**IM 30**	**IM 7**	**IM 5**	**Sum of scores**
Demonstrated	1.1				1	1	1	1	1		1	6
behaviours	1.2	1	1	1						1		4
	2.1						1					1
Round 1	2.2				1	1		1		1	1	5
	3		1							1		2
	4	1				1	1	1	1		1	6
	5	1				1		1				3
	6	1				1	1	1	1	1	1	7
Demonstrated	1.1				1	1	1	1	1		1	6
behaviours	1.2	1	1	1						1		4
	2.1						1					1
	2.2				1	1		1		1	1	5
Round 2	3									1		1
	4	1				1	1	1	1		1	6
	5	1				1		1				3
	6	1				1	1	1	1	1	1	7

*Behaviour codes are derived from Table 5.2: 1.1) minimum six consecutive corners, 1.2) cutting of three non-consecutive corners, 2.1) minimum six consecutive margins, 2.2.) minimum of three non-consecutive margins, 3) initial tip and base cutting, 4) 30 sec scraping to remove foam, 5) two repetitions of scraping and tip and base cutting and 6) final shaping via scraping.

B2) Intra-rater reliability test results from 10 random videos in the emulation condition

Videos

	*Codes	**EM 8**	**EM 3**	**EM 12**	**EM 28**	**EM 26**	**EM 10**	**EM 29**	**EM 15**	**EM 3**	**EM 30**	**Sum of scores**
Demonstrated	1.1											0
behaviours	1.2			1		1	1					3
	2.1											0
	2.2			1	1	1					1	4
Round 1	3											9
	4				1	1						2
	5											0
	6			1	1	1						3
Demonstrated	1.1											0
behaviours	1.2			1		1	1					3
	2.1		1									1
	2.2				1	1					1	3
Round 2	3											0
	4				1	1						2
	5											0
	6			1	1	1						3

*Behaviour codes are derived from Table 5.2: 1.1) minimum six consecutive corners, 1.2) cutting of three non-consecutive corners, 2.1) minimum six consecutive margins, 2.2.) minimum of three non-consecutive margins, 3) initial tip and base cutting, 4) 30 sec scraping to remove foam, 5) two repetitions of scraping and tip and base cutting and 6) final shaping via scraping.

B3) Fidelity codes (original coding system) for all participants in the emulation and imitation condition.

Participant	**Fidelity coding system**	
	Emulation	Imitation
1	0	0
2	0	4
3	0	4
4	0	4
5	0	3
6	0	4
7	0	3
8	0	1
9	1	4
10	0	1
11	0	4
12	2	3
13	0	2
14	1	3
15	0	0
16	0	0
17	0	2
18	0	3
19	2	4
20	3	2
21	0	3
22	1	4
23	0	1
24	0	3
25	2	5
26	3	2
27	2	1
28	2	2
29	0	4
30	0	1