

1 Differential cultural reproduction of skill level and mental
2 templates in Late Acheulean handaxe morphology:
3 Archaeological and experimental insights

4 Cheng Liu* Nada Khreisheh† Dietrich Stout‡ Justin Pargeter§

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6 **Abstract**

7 Despite the extensive literature focusing on Acheulean handaxes, especially the sources
8 and meaning of their morphological variability, many aspects of this topic remain elusive.
9 Archaeologists cite many factors that contribute to the considerable variation of handaxe
10 morphology, including knapper skill levels and mental templates. Integrating these two lines
11 of literature into a broader theoretical framework of cultural reproduction, here we present
12 results from a multidisciplinary study of Late Acheulean handaxe-making skill acquisition
13 involving thirty naïve participants trained for up to 90 hours in Late Acheulean style handaxe
14 production and three expert knappers. We compare their handaxe to the Late Acheulean
15 handaxe assemblage from Boxgrove, UK. Through the principal component analysis of mor-
16 phometric data derived from images, our study suggested that knapper skill levels and mental
17 templates have a relatively clear manifestation in different aspects of handaxe morphology.
18 The former relates to cross-sectional thinning (PC1), while the latter refers to handaxe elon-
19 gation and pointedness (PC2). Moreover, we also evaluated the effects of training on the
20 differential cultural reproduction of these two aspects using the data from a 90-hour-long
21 knapping skill acquisition experiment. We found that the desired shape of a handaxe can
22 be relatively quickly picked up by novices, while reaching the skill level of modern experts
23 requires more training time than was permitted in this extensive and long-running training
24 program. ¶

25 ¶ **Keywords:** Late Acheulean; Handaxe morphology; Boxgrove; Experimental archaeology;
26 Skill level; Mental template; Cultural transmission

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*Department of Anthropology, Emory University, Atlanta, GA, USA; raylc1996@outlook.com

†The Ancient Technology Centre, Cranborne, Dorset, UK; nada.khareisheh@dorsetcouncil.gov.uk

‡Department of Anthropology, Emory University, Atlanta, GA, USA; dwstout@emory.edu

§Department of Anthropology, New York University, New York, NY, USA; Rock Art Research Institute, School of Geography, Archaeology, and Environmental Studies, University of the Witwatersrand, Johannesburg, South Africa; justin.pargeter@nyu.edu

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46 **1 Introduction**

47 The morphological variability of Acheulean handaxes has been one of the most well-studied
 48 and well-published topics in paleolithic archaeology (Key & Lycett, 2019; Petraglia & Korisettar,
 49 1998; White, 1998). Despite the recurrent narrative emphasizing the homogeneity and longevity
 50 of handaxe assemblages on a global scale and the conservatism behind this phenomenon that
 51 evokes genetic explanations (Corbey et al., 2016; Corbey, 2020; Richerson & Boyd, 2005; Sterelny,
 52 2004), many researchers have recognized the diversity within what has been deemed as a unified
 53 Acheulean “tradition” and tried to dissect the sources and meaning of this variation (Lycett &
 54 Gowlett, 2008; Moncel et al., 2018b, 2018c, 2018a; Nowell, 2002; Nowell & White, 2010; Sharon et al.,
 55 2011). More specifically, a complex suite of interconnecting factors (Lycett & Cramon-Taubadel,
 56 2015) have been identified to contribute to handaxe morphological variation, including but not
 57 limited to raw material variability (Eren et al., 2014; Lycett et al., 2016; McNabb & Cole, 2015;
 58 Sharon, 2008), percussor properties (Shipton et al., 2009), functional differences (Key et al., 2016;
 59 Key & Lycett, 2017; Lycett & Gowlett, 2008; Machin et al., 2007; White & Foulds, 2018), reduction
 60 method/intensity (Shipton et al., 2009; Shipton & Clarkson, 2015), time budgets (Schillinger et
 61 al., 2014b), learning processes (Kempe et al., 2012; Lycett et al., 2016), social signaling (Kohn &
 62 Mithen, 1999; Spikins, 2012), aesthetic preferences (Gowlett, 2021; Le Tensorer, 2006), knapper

63 skill levels (Caruana & Herries, 2021; Herzlinger et al., 2017; Stout et al., 2014), and mental
64 templates (García-Medrano et al., 2019; Hutchence & Scott, 2021; Schillinger et al., 2017). From
65 this extensive list, knapper skill levels and mental templates have been repeatedly mentioned
66 and discussed in the now extensive corpus of handaxe studies, and Boxgrove handaxes have been
67 one of the most studied assemblages from these two angles. Of particular attention here are the
68 experimental works conducted by Stout et al. (2014) focusing on inferring knapping skill level
69 and Garcia-Medrano et al. (2019) identifying the mental template of the Boxgrove assemblage.
70 Our paper incorporates these two perspectives into a broader conceptual framework of cultural
71 reproduction and provides novel insights to the same archaeological assemblage by comparing it
72 with experimentally made handaxes.

73 **1.1 Mental template**

74 In its classical definition, the term mental template indicates that the “idea of the proper form
75 of an object exists in the mind of the maker, and when this idea is expressed in tangible form in
76 raw material, an artifact results” (Deetz, 1967: 45). This concept lies at the very foundation of the
77 cultural-historical approach in that the identification of archaeological cultures is based on the
78 existence of distinct mental templates in a given spatial-temporal framework. Early researchers,
79 whether explicitly or implicitly, often endorsed this conceptual framework and actively applied it
80 in the typological analysis of handaxes at the regional level (Roe, 1969; Wenban-Smith et al., 2000;
81 Wenban-Smith, 2004). Combined with the production of large flakes, the emergence of mental
82 templates (or “imposed form”) has been recognized as a major technological innovation of the
83 Acheulean compared with the Oldowan (Isaac, 1986). For a decade or so, this concept has been
84 less frequently used, since it was criticized for a) its normative and static assumption (Lyman
85 & O’Brien, 2004), b) ignoring other competing factors such as raw material constraints (White,
86 1995), and c) being constrained by the basic fracture mechanics and design space of bifacial
87 technology (Moore, 2011; Moore & Perston, 2016). To avoid the historical baggage associated
88 with this controversial term, some researchers developed alternative frameworks such as “design
89 imperatives” derived from utilitarian and ergonomic principles, which refers to a set of minimum
90 features shared by all handaxes including their glob-but, forward extension, support for the
91 working edge, lateral extension, thickness adjustment, and skewness (Gowlett, 2006; Wynn &
92 Gowlett, 2018). The major difference between the concepts of design imperatives and mental
93 templates lies in the fact that the former does not necessarily require the presence of explicit

internal representations of form, where the shape of handaxes can instead emerge “through the coalescence of ergonomic needs in the manipulation of large cutting tools (Wynn, 2021: 185).”

Recently, researchers have actively addressed the above-mentioned critiques and reconceptualized the concept of mental template in the study of handaxe morphology. Regarding the normative and static assumptions, Hutchence and Scott (2021), for example, leveraged the theory of “community of practice” (Wenger, 1998) to explain the stability of Boxgrove handaxe design across multiple generations. From this perspective, social norms behind the consolidated material expressions were developed and negotiated by individuals in a group who have a shared history of learning. They further emphasized that emergent actions of individual knappers also contribute greatly to the shape of Boxgrove handaxes but they were simultaneously constrained by the imposition of social norms. This view also somewhat echoes the “individualized memic construct” proposed by McNabb et al. (2004), which highlighted the influence of individual agency that is complementary to the traditionally favored explanation of social learning. As for the critique towards confounding factors explaining morphological variability, raw material is often treated as an important variable to be controlled at the very beginning of a research design focusing on mental templates. This is best exemplified by an experimental study of García-Medrano et al. (2019), where they carefully chose experimental nodules mirroring those found in the Boxgrove archaeological assemblage in composition, size, and shape. Regarding the critique of design space constraint, Moore and Perston’s experiment (2016) suggested that bifaces can be manufactured through flake removals dictated by a random algorithm. However, Moore (2020: 656-657) also suggested that these random experiments cannot produce “attributes like the congruent symmetries of handaxes seen in the Late Acheulean.” In short, when exercised with proper caution, the concept of mental templates still has its value in our study of handaxe morphological variation, which can be further dissected into a series of shape variables corresponding to pointedness, elongation, and cross-sectional thinning among other things.

1.2 Skill level

Following the reconceptualization of the mental template as a more flexible and interactive concept, one possible way of defining skill is the capacity for a knapper to realize mental templates using the resources available (Roux et al., 1995: 66). This version of conceptualization, particularly relevant when it comes to motor skills such as knapping, can be dismantled into two mutually

dependent aspects, namely the intentional aspect (goal/strategic planning) and the operational aspect (means/motor execution) (Connolly & Dalgleish, 1989). It also roughly corresponds to the well-known dichotomy developed by French lithic analysts of “*connaissance*” (abstract knowledge) and “*savoir-faire*” (practical know-how) (Pelegrin, 1993). As Stout (2002: 694) noted, the acquisition of skill is deeply rooted in its social context, and it is not composed of “some rigid motor formula” but “how to act in order to solve a problem”. This ecological notion of skill somewhat mirrors Hutchence and Scott’s (2021) reconceptualization of the mental template in that they both refute the idea that technology is simply an internal program expressed by the mind and they prefer a dynamic approach emphasizing the interaction between perception and action. The manifestations of skill in materialized form display a great amount of variation, but ethnoarchaeological studies have repeatedly suggested that skills can be improved through practice as perceived by local practitioners. It is thus possible to evaluate the skill levels reflected in knapping products (Roux et al., 1995; Stout, 2002). When contextual information is less readily available as in the Late Acheulean archaeological assemblages, how to properly operationalize and measure knapping skills has been a methodological issue receiving much attention among archaeologists (Bamforth & Finlay, 2008; Kolhatkar, 2022). In addition to measurements that can be almost applied in any lithic technological system such as raw materials, platform preparation, as well as hinges, in the context of handaxe technology, symmetry (Hodgson, 2015; Hutchence & Debackere, 2019) and cross-sectional thinning (Caruana, 2020; Pargeter et al., 2019; Stout et al., 2014; Whittaker, 2004: 180-182) have been frequently quoted as reliable and distinctive indicators of the skill level as supported by several experimental studies. These two features have also been commonly used as standards for dividing Early Acheulean and Late Acheulean (Callahan, 1979; Clark, 2001; Schick & Toth, 1993).

1.3 Cultural reproduction

The cultural reproduction, or cultural transmission as described in standard cultural evolutionary literature (Eerkens & Lipo, 2005, 2007), of mental templates and skill levels makes them reach beyond individual-level practice and form a repetitive pattern that can be identified in archaeological records. Nonetheless, the abstract shape of handaxe as a mental template that is often pulled away from its original substrate has been frequently treated as the main research subject of cultural transmission experiments (Schillinger et al., 2014b, 2017, 2015), while how knapping skill as another source of variation is reproduced during the learning process and how it moderates

155 the material manifestation of mental templates has been rarely discussed. The ignorance of
156 the latter becomes one of motivations behind our terminological choice of “reproduction” over
157 “transmission”, where the former implies more than just the copying of an static image with
158 information loss ([Liu & Stout, 2022](#); [Stout, 2021](#)). This reframing essentially echoes the stance of
159 extended evolutionary synthesis (EES) on inclusive inheritance that phenotypes are not inherited
160 but reconstructed in development ([Laland et al., 2015](#): 5), which has also received more attention
161 recently in the domain of cultural evolution ([Charbonneau & Strachan, 2022](#); [Strachan et al.,](#)
162 [2021](#)).

163 Centering around the concept of cultural reproduction, we aim to explore the possibility of
164 dissecting the interaction of skill level and mental template through a comparative study of
165 an archaeological handaxe assemblage known for its remarkable high skill level, a reference
166 handaxe collection produced by modern knapping experts, and an experimental handaxe sample
167 produced by modern novice knappers. We generated the novice handaxe collection from a
168 90-hour skill acquisition experiment providing the opportunity to introduce the diachronic
169 dimension of training time and interrogate its impact on the variables of interest. As such, we
170 propose the following two interconnected research questions in this article: 1) Can skill level
171 and mental templates be efficiently detected from handaxe morphometric data? Accordingly, we
172 predict that the morphometric variables showing overlap between Boxgrove and expert samples
173 while being markedly different from novice samples reflect skill level differences, and all three
174 group should show a similar mental template since this is a common target. 2) Does training
175 has a differential effect in terms of the reproduction of skill level and mental templates among
176 novices? Our hypothesis is that throughout the training the novice samples should become more
177 similar to expert samples in both skill level and mental template, but the acquisition of the former
178 aspect will be more challenging and thereby slower than the latter aspect. This hypothesis is
179 informed by the previous study of Pargeter et al. ([2020](#)) showing that in handaxe manufacture
180 novices’ predictions of the contour of flakes to be removed are highly similar to those of expert
181 knappers, while novices do not have the right forces and accuracy to successfully remove their
182 target flakes to produce a nice handaxe.

¹⁸³ **2 Materials and methods**

¹⁸⁴ **2.1 Boxgrove handaxe collection**

¹⁸⁵ The archaeological site of Boxgrove is located in the former Eartham quarry, Boxgrove, West Sussex,
¹⁸⁶ featuring a long sequence of Middle Pleistocene deposits (Pope et al., 2020; Roberts & Parfitt,
¹⁸⁷ 1998). This 500-ka-old site has documented exceedingly rich details of Lower Paleolithic hominin
¹⁸⁸ subsistence behaviors (Smith, 2013, 2012) and their paleoenvironmental contexts (Holmes et
¹⁸⁹ al., 2010; Preece & Parfitt, 2022). In addition to the presence of one of the earliest hominin fossil
¹⁹⁰ (tentatively assigned to *Homo heidelbergensis*, Hillson et al., 2010; Lockey et al., 2022; Roberts et
¹⁹¹ al., 1994) and bone assemblages with anthropogenic modifications in northern Europe (Bello
¹⁹² et al., 2009), Boxgrove is mostly known for its large sample size of Late Acheulean-style flint
¹⁹³ handaxes and the high skill level reflected in their manufacture (Figure 1). As such, it has received
¹⁹⁴ wide research attention in the past two decades regarding the relationships between technology,
¹⁹⁵ cognition, and skills (García-Medrano et al., 2019; Iovita et al., 2017; Iovita & McPherron, 2011; Key,
¹⁹⁶ 2019; Shipton & Clarkson, 2015; Stout et al., 2014). To identify the morphological manifestation of
¹⁹⁷ knappers' skill level in our study, we selected a complete handaxe assemblage (n=326) previously
¹⁹⁸ analyzed and reported in digital formats by Iovita and McPherron (2011), which is currently
¹⁹⁹ curated at the Franks House of the British Museum (Iovita et al., 2017). The digital photographs
²⁰⁰ are taken of each handaxe at a 90° angle, which was oriented with the tip to the right of the photos,
²⁰¹ and the camera faces the most convex surface of the handaxe (Iovita & McPherron, 2011).

Boxgrove



Expert



— 5 cm —

Novice



Figure 1: A selection of Boxgrove handaxes and modern replicas produced by experts and novices.

202 **2.2 Experimental handaxe collection**

203 The handaxe experimental replicas used in this study comprised two sub-collection ([Figure 1](#)).
204 The first sub-collection includes 10 handaxes knapped by three expert knappers, including Bruce
205 Bradley (n=4), John Lord (n=3), and Dietrich Stout (n=3) ([Stout et al., 2014](#)). These handaxes
206 were made for previous research projects, which similarly aimed to approximate ‘Late Acheulean’
207 handaxes explicitly comparable to the Boxgrove assemblage ([Faisal et al., 2010; Stout et al., 2014;](#)
208 [Stout et al., 2011](#)). The second sub-collection is produced from a 90-hour handaxe knapping skill
209 acquisition experiment ([Bayani et al., 2021; Pargeter et al., 2020; Pargeter et al., 2019](#)), where 30
210 adults with no previous experience in knapping were recruited from Emory University and its
211 surrounding communities and requested to make 132 handaxes in total. Among these 30 adult
212 participants, 17 have gone through multiple one-to-one or group training sessions that amounted
213 to 89 hours in maximum, while the remaining 13 were assigned to the controlled group, where
214 no formal training is given. As part of the preparation efforts, the experimental team spalled
215 the Norfolk flints acquired through [Neolithics.com](#) into flat blanks of similar size and shape for
216 training and assessments. The mechanical properties of these raw materials are comparable to
217 the ones used in Boxgrove in that they are both fine-grained and highly predictable in fracturing
218 process.

219 In the knapping skill acquisition experiment, all research participants participated in the initial
220 assessment (assessment 1 in our data set) before formal training, where they each produced a
221 handaxe after watching three 15-minute videos of Late Acheulean style handaxes demonstrated
222 by expert knappers and examining four Late Acheulean style handaxe replicas from our expert
223 sample. Training was provided by verbal instruction and support from the second author, an
224 experienced knapping instructor ([Khreisheh et al., 2013](#)) with 10 years knapping practice and
225 specific knowledge of Late Acheulean technology including the Boxgrove handaxe assemblage.
226 She was present at all training sessions to provide help and instruction to participants. All train-
227 ing occurred under controlled conditions at the outdoor knapping area of Emory’s Paleolithic
228 Technology Lab, with knapping tools and raw materials provided. All participants were instructed
229 in basic knapping techniques including how to select appropriate percussors, initiate flaking
230 on a nodule, maintain the correct flaking gestures and angles, prepare flake platforms, visualize
231 outcomes, deal with raw material imperfections, and correct mistakes. Handaxe-specific instruc-
232 tion included establishment and maintenance of a bifacial plane, cross-sectional thinning, and

233 overall shaping. The training emphasized both aspects of handaxe making technical skill (the
234 importance of producing thin pieces with centered edges) as well as mental template related
235 markers (symmetrical edges).

236 Subsequently, the 17 participants in the experimental group were assessed after every ten hours
237 of the cumulative learning period, where each of them was requested to produce a handaxe for
238 expert knapper's (N. Khreisheh) review, leading to the compilation of a data set composing 9
239 assessments in total. It should be also noted that 6 out of 17 participants dropped out of the
240 research before the final assessment due to personal reasons. To detect the effect of training
241 on skill level and mental template, we reorganized our assessment classification scheme and
242 combined it into three broader categories, namely pre-training (assessment 1), early training
243 (assessment 2-5), and late training (assessment 6-9), which helps increase the sample size of
244 the measured intervals. A more detailed experimental protocol can be assessed in one of our
245 published papers ([Pargeter et al., 2019](#)).

246 2.3 Lithic analysis

247 To better understand the morphological variation of Boxgrove handaxe collection, we adopted a
248 standardized analytical procedure to extract the morphometric information from 752 photos of
249 the studied samples ([Iovita & McPherron, 2011](#)), which include both the front and lateral views
250 of a given specimen. First, we used Adobe Photoshop to conduct a batch transformation of
251 the samples' pixel scale into a real-world measurement scale based on the fixed photographic
252 setting. This is then followed by the batch conversion of color photographs to a black-and-white
253 binary format. Subsequently, we cropped the silhouettes of handaxes one by one using the
254 Quick Selection Tool in Adobe Photoshop. The metric measurements were conducted in ImageJ
255 ([Rueden et al., 2017](#)), where we employed a custom ImageJ script ([Pargeter et al., 2019](#)) to mea-
256 sure the maximum length, width, and thickness of a given silhouette. The width and thickness
257 measurements are taken at 10% increments of length starting at the tip of each handaxe (**Figure**
258 [2](#)), which eventually leads to 19 morphometric variables in total (1 length measurement, 9 width
259 measurements, and 9 thickness measurements). Finally, we calculated the geometric means of all
260 19 linear measurements to create a scale-free data set that preserves the individual morphological
261 variation at the same time ([Lycett et al., 2006](#)). This allometric scaling procedure controls for size
262 variation which may come from initial blanks and/or reduction intensity (shaping/resharpening).

263 Notably, Shipton and Clarkson (2015) previously found that reduction intensity does not have a
264 strong impact on the shape of handaxes. The same procedure was also applied to the morphome-
265 tric analyses of the experimental handaxe collection, which was partially published in Pargeter et
266 al. (2019).

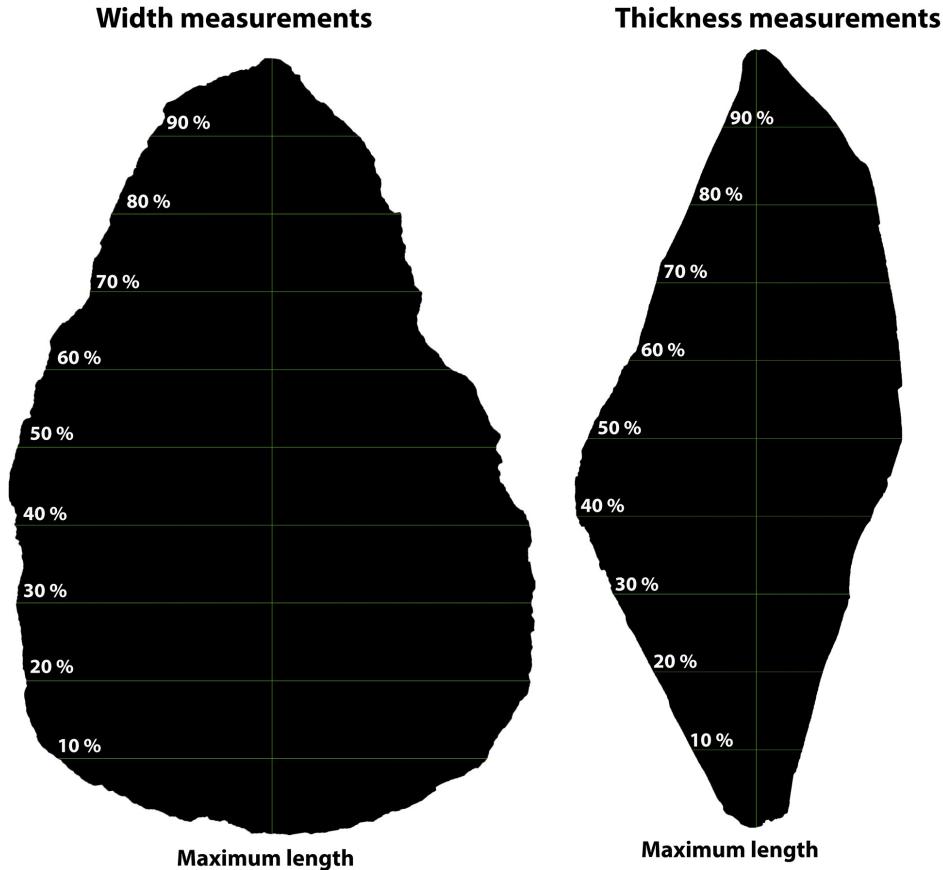


Figure 2: A visual demonstration of the handaxe measurement protocol using Image J (after Pargeter et al. 2019: Figure 5).

267 2.4 Statistical analyses

268 We use the statistical programming language R 4.1.1 (R Core Team, 2021) to conduct statistical
269 analyses and data visualization in this study, particularly the R packages “FactoMineR” (Lê et
270 al., 2008) and “ggstatsplot” (Patil, 2021). As the initial step, simple visualization techniques such
271 scatter plots are frequently used to explore the relationships between variables of interest. Given
272 the number of variables involved in this study, we used principal component analysis (PCA) to
273 reduce the dimension and identify the possible patterns in this morphometric data set, which
274 is one of the most used techniques in similar studies (García-Medrano, Maldonado-Garrido,
275 et al., 2020; García-Medrano, Ashton, et al., 2020; Herzlinger et al., 2017; Iovita & McPherron,

276 2011; Shipton & Clarkson, 2015; Stout et al., 2014). To detect the effect of training on novices' 277 performance as compared with archaeological samples and handaxe made by experts, we also 278 compare the corresponding metrics built on PCA across different training periods and across all 279 groups using the Games-Howell nonparametric post-hoc test. Compared with other nonpara- 280 metric tests frequently used in archaeological research for multiple group comparison such as 281 Tukey's test, Games-Howell test does not rely on the assumptions of sample normality, and equal 282 sample sizes and equal variance are not necessary conditions to perform this test. The sample 283 size of each compared group can be as low as 6 (Games & Howell, 1976; Sauder & DeMars, 2019). 284 Lastly, we compare the delta weight, as defined by the difference between initial nodule weight 285 and end product weight, between these groups to understand the effect of reduction intensity 286 on morphological variation. This study adheres to the principles of reproducibility and data 287 transparency of archaeological research by depositing all the codes and data sets involved in an 288 open-access online repository (Marwick, 2017), which are available as supplementary materials 289 and can be accessed through the author's Github (<https://github.com/Raylc/Boxgrove-Exp>).

290 3 Results

291 3.1 Principal component analysis

292 Our analysis suggested that the first two components already explain 77.2% of the variation for the 293 entire morphometric data set composed of 19 variables (Figure 3), which is a rather reasonable 294 variance ratio to avoid overfitting. Variable loadings (Table 1) indicate that the first principal 295 component (PC1) captures relative cross-sectional thickness ("refinement"). It is positively corre- 296 lated with all thickness measurements while negatively correlated with all other measurements. 297 A higher PC1 value thus indicates a handaxe that is thicker relative to width and length, and vice 298 versa. The second principal component (PC2) tracks elongation and pointedness, as indicated 299 by a positive covariance of maximum length and bottom width/thickness. As PC2 increases, a 300 handaxe will be relatively longer and more convergent from the broad base to the tip. Thus, PC1 301 corresponds to cross-sectional thinning and PC2 to a narrowing of the tip relative to length and 302 base dimensions.

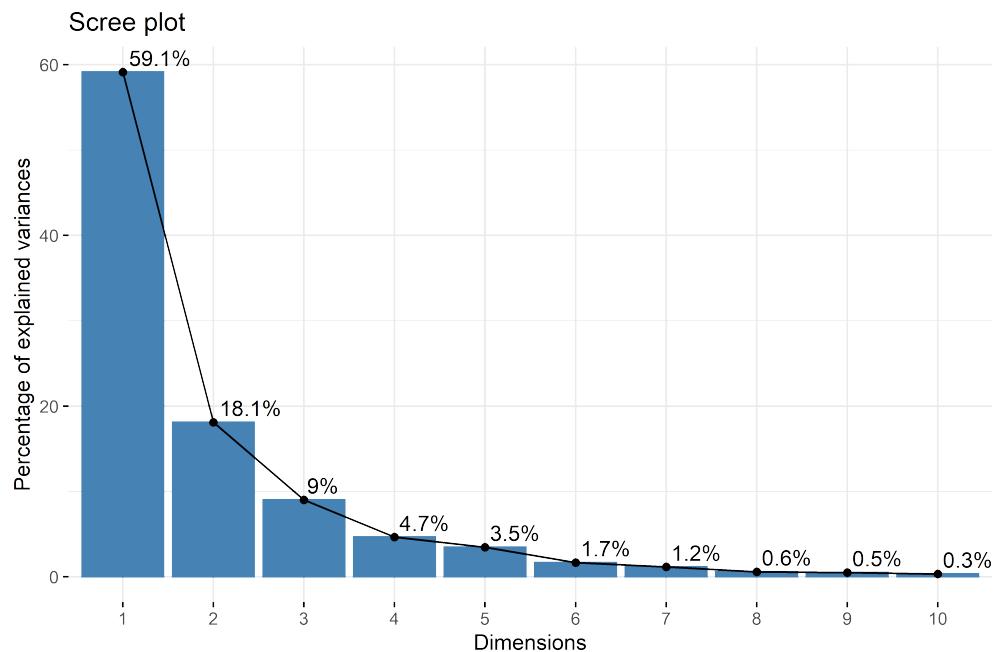


Figure 3: A scree plot showing the percentage of explained variances of the first 10 principal components.

Table 1: Variable loadings for the first two principal components. PC1 (Dim.1) is positively correlated with all thickness-related variables and negatively correlated with all width-related variables and the maximum length. PC2 (Dim.2) is positively with bottom width and thickness variables as well as the maximum length and negatively correlated with width and thickness variables of the tip area.

Variables	Dim.1	Dim.2
width_90%	-0.1131	-0.1256
width_80%	-0.1420	-0.1327
width_70%	-0.1684	-0.1232
width_60%	-0.1867	-0.0967
width_50%	-0.2037	-0.0652
width_40%	-0.2121	-0.0197
width_30%	-0.2083	0.0233
width_20%	-0.1886	0.0661
width_10%	-0.1447	0.0806
thickness_90%	0.0143	-0.0240
thickness_80%	0.0247	-0.0227
thickness_70%	0.0436	-0.0094
thickness_60%	0.0668	0.0048
thickness_50%	0.0894	0.0261
thickness_40%	0.1083	0.0485
thickness_30%	0.1288	0.0629
thickness_20%	0.1444	0.0659
thickness_10%	0.1309	0.0487
max_length	-0.3626	0.2507

303 A closer look at the principal component scatter plot ([Figure 4](#)) yields the clustering of different
 304 groups of handaxes. The majority of Boxgrove handaxes occupy an area featuring negative values
 305 of both PC1 and PC2. The expert group is similar to the Boxgrove group in PC1, while the former
 306 has a relatively higher PC2 value than the latter on average. The group of novice displays the
 307 highest ranges in both PC1 and PC2 values according to the scatter plot, however, it is rather
 308 pronounced that most handaxes made by novices have a positive PC1 value that is different from
 309 both the groups of Boxgrove and experts.

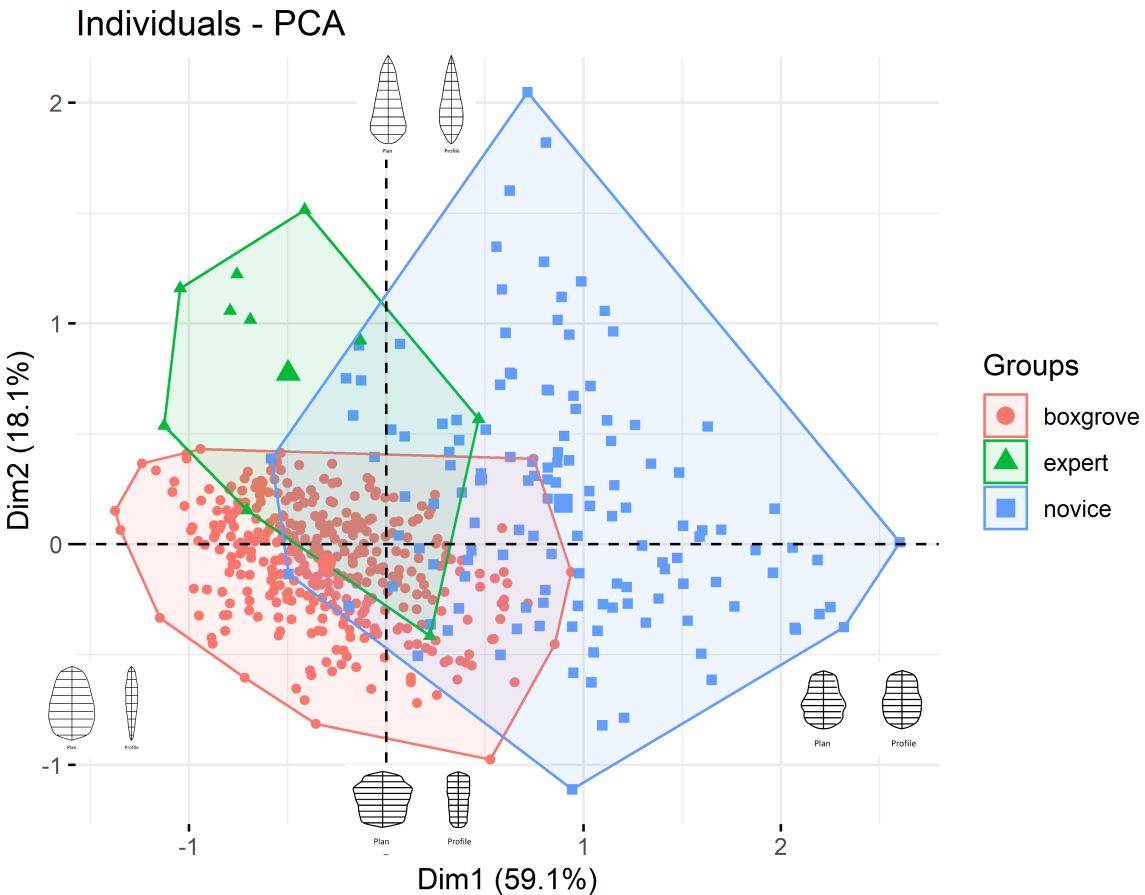


Figure 4: A principal component scatter plot of handaxes from the groups of Boxgrove (red, n=326), expert (green, n=10), and novice (blue, n=132). The four images illustrate simplified plan and profile morphology of handaxes displaying extreme PC values (e.g., The leftmost and uppermost handaxes respectively display the highest PC1 and PC2 value, and vice versa).

310 In addition, visual inspection of the principle component scatter plot (Figure 4) suggested that
 311 PC1 and PC2 might be negatively correlated within the Boxgrove and Expert groups. To test this,
 312 we conducted a series of exploratory plotting and statistical analyses of the PC values of three
 313 groups analyzed in our analysis (Figure 5). Across all three groups, a negative correlation has
 314 been displayed between the PC1 and PC2 values, although this trend is not statistically significant
 315 ($r=-0.41, p= 0.24$) in the expert group, probably because of its small sample size.

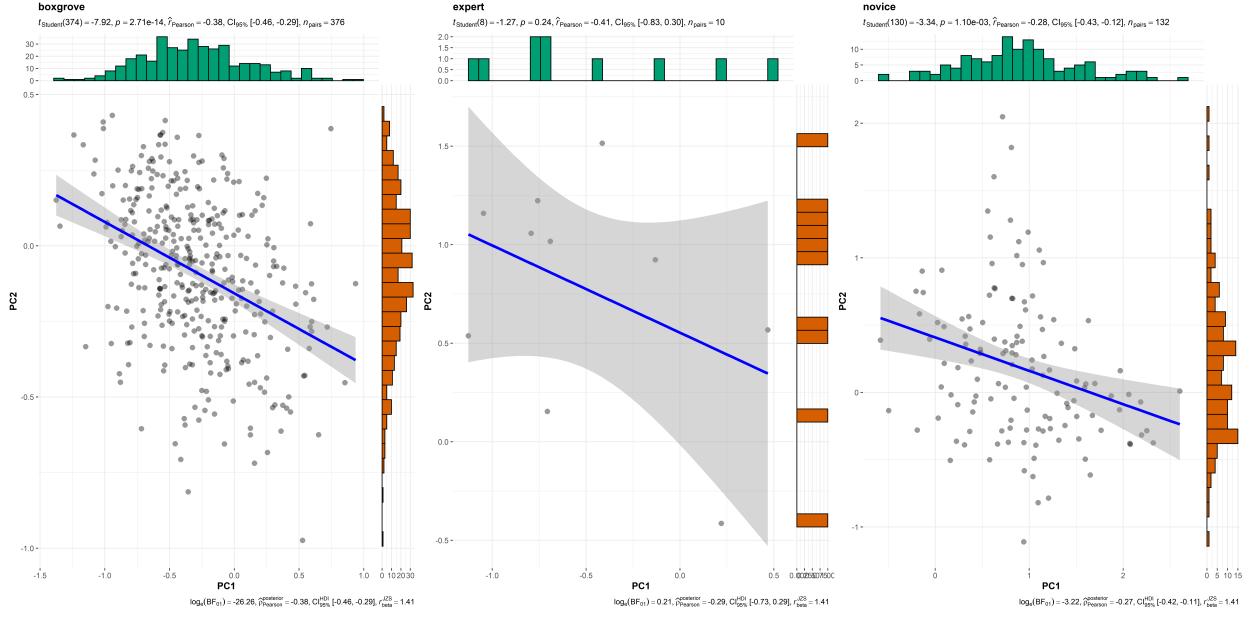


Figure 5: A scatter plot showing the correlation between PC1 and PC2 respectively in the groups of Boxgrove (left, $n=326$), expert (middle, $n=10$), and novice (right, $n=132$). The upper left area in each individual plot displays statistical reporting from a frequentist perspective, including the student-t test statistics, p-value, Pearson correlation coefficient, confidence interval, and sample size. The lower right area in each individual plot displays statistical reporting from a Bayesian perspective, including the natural logarithm of Bayes factor, posterior type and estimate, credible interval, and prior type and value.

316 3.2 Effects of training

317 We extracted the PC1 and PC2 values of individual handaxes and compared them between
 318 different groups, where the novice group was divided into three sub-groups based on their
 319 training stages as specified in the method section. As such, we found that for PC1 values (**Figure**
 320 **6**), the only two group comparisons that are **not** statistically significant are the one between
 321 Boxgrove and Expert ($t = -1.65, p > 0.05$) and the one between Early training and Late training
 322 stages ($t = -0.649, p > 0.05$), which at least partially confirms our visual observation of the
 323 general PCA scatter plot. Likewise, for PC2 values (**Figure 7**), the group comparison between
 324 the Early training and Late stages again is not statistically significant ($t = 0.333, p > 0.05$). An
 325 unexpected result is that the mean PC2 value difference between the Pre-training group and
 326 Boxgrove is also not statistically significant ($t = -0.818, p > 0.05$). These results essentially
 327 suggest that there is a significant difference between the pre-training group and post-training
 328 groups in both PC1 (thinning) and PC2 (pointedness). However, the effects of training across
 329 different assessment periods on both dimensions are not significant. Regarding the delta weight
 330 of different groups, our analysis (**Figure 8**) suggests that there is a significant difference between
 331 the pre-training group and Late training group, while all other pairwise group comparison results

332 are insignificant. It can also be inferred that the expert group display a higher variability in terms
 333 of delta weight compared with novices.

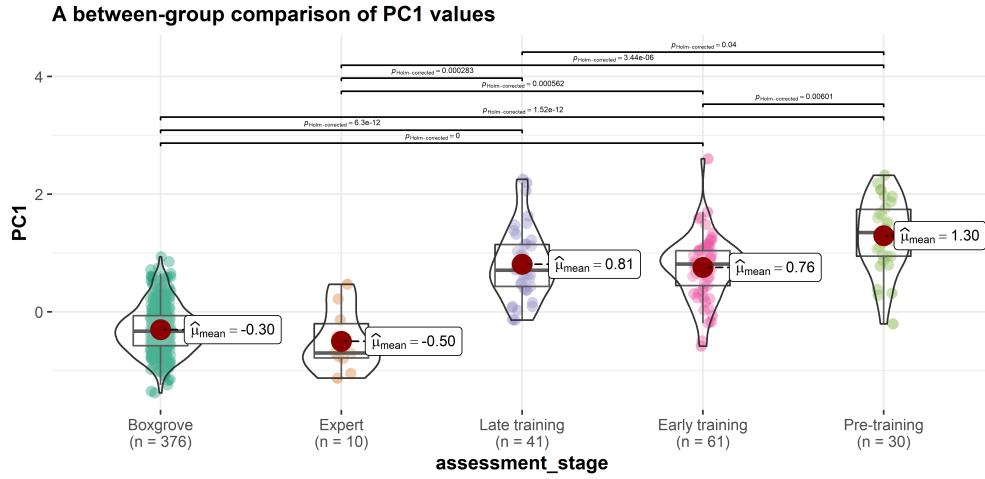


Figure 6: A between-group comparison of PC1 values.

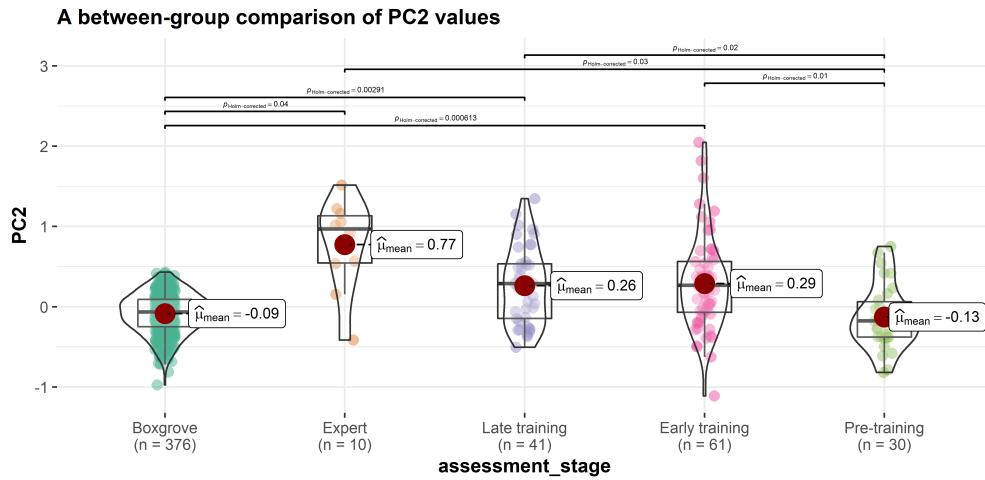


Figure 7: A between-group comparison of PC2 values.

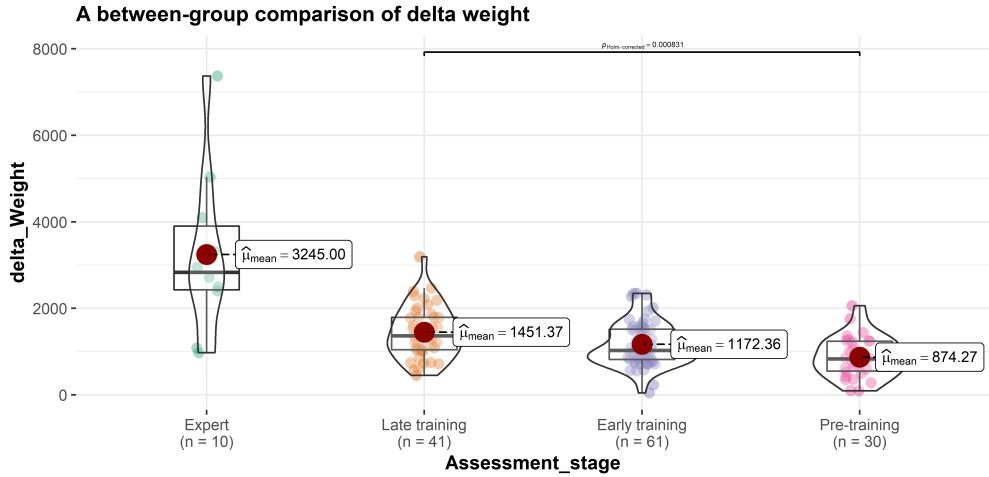


Figure 8: A comparison of the delta weight between the pre-training, early training, late training, and the expert group.

334 4 Discussion

335 Our study suggests that both skill level and mental template have a relatively clear manifestation in
 336 different aspects of handaxe morphology, where the former is related to cross-sectional thinning
 337 (PC1) while the latter relates to handaxe elongation and pointedness (PC2). Moreover, we also
 338 evaluated the differential effects of training using the data from a 90-hour long knapping skill
 339 acquisition experiment and confirmed the previous finding (2019) that reaching the skill level
 340 of modern experts requires more training time than was permitted in this extensive and long-
 341 running training program. In accordance with the existing literature on handaxe knapping skill
 342 (Callahan, 1979; Caruana, 2020; Stout et al., 2014), the results of PCA suggested that PC1 (cross-
 343 sectional thinning) is a robust indicator of skill level as it is a common feature shared by modern
 344 expert knapper and Boxgrove knappers. Thinning is regarded as a technique requiring a high
 345 knapping skill level because it requires one to carefully detach flakes in an invasive manner
 346 while not breaking the handaxe into several pieces, serving the purpose of achieving the desired
 347 convexity and/or volume. This procedure involves precise control of striking forces, strategic
 348 choice of platform external angle, and attentive preparation of bifacial intersection plane, all of
 349 which were part of our experimental training program (Callahan, 1979; Caruana, 2022; Pargeter
 350 et al., 2020; Shipton et al., 2013; Stout et al., 2014). Experimental studies have also shown that
 351 the thinning stage of handaxe produce often involves the use of soft hammers, which is also
 352 supported by indirect archaeological evidence of flake attributes from Boxgrove (Roberts & Parfitt,

353 1998: 384-394; [Roberts & Pope, 2009](#)), although the validity of differentiating purcussor types
354 (hard hammerstone, soft hammerstone, and antler hammer) based on flake attributes has been
355 challenged by other experimental studies([Driscoll & García-Rojas, 2014](#)). It should be noted that
356 both our experts and novices frequently used soft hammers in the production of experimental
357 assemblages. In the skill acquisition experiments, novice knappers were explicitly taught to
358 switch to the soft hammer for thinning purposes, but some of them did not follow the instruction
359 during the assessment. On the other hand, it has also been shown that hard hammers can also
360 be used to achieve similar thinning results ([Bradley & Sampson, 1986](#); [Pelcin, 1997](#)), and the
361 replicas produced by Bruce Bradley in our expert reference collection did not involve the use of
362 soft hammers.

363 Given the dissimilarity of PC2 (elongation and pointedness) values between archaeological and
364 experimental samples and its similarity among modern knappers, we argue that this dimension
365 reflects different mental templates, where the Boxgrove assemblage displays an ovate shape
366 featuring a wider tip while the experimental assemblages are characterized by a more pointed
367 shape with a longer central axis. It should be noted that a thin cross section as measured by
368 PC1 could also be part of a mental template or design target and was explicitly instructed by
369 our expert instructor to novices, however, novices cannot fully understand nor achieve this
370 technological goal due to the constraint of skill level, making it a robust indicator of the latter.
371 Our results regarding the ovate plan morphology of the Boxgrove assemblage generally supports
372 what have been reported by Shipton and White ([2020](#)) as well as Garcia-Medrano et al. ([2019](#)).
373 The finding that the expert group has a mental template different from the Boxgrove assemblage
374 is rather surprising since they were requested to mimic Boxgrove handaxes, a potential reason
375 of which could be that these expert didn't have Boxgrove handaxes at hand as model during the
376 manufacture and thus followed their vague memory of a "representative teardrop Late Acheulean
377 handaxe." In general, this pattern may reflect a divergence of group-level aesthetic choices as
378 expected under the theoretical framework of the communities of practice ([Wenger, 1998](#)), which
379 could potentially provide an mechanistic explanation to some macro-level cultural phenomena
380 such as regionalization ([Ashton & Davis, 2021](#); [Davis & Ashton, 2019](#); [García-Medrano et al.,](#)
381 [2022](#); [Shipton & White, 2020](#)). The most common form of learning in the experiment occurred in
382 the group condition, where the instructor, as the competent group member, directed the joint
383 enterprise through actively teaching multiple novices at the same time. Meanwhile, novices had
384 the chance to also communicate and learn from their peers, producing a shared repertoire of

385 artifacts and actions. Unfortunately, the handaxe data from the instructor (N. Khreisheh) are
386 unavailable, but it should be noted that the instructor has learned how to knap and how to teach
387 knapping from one of our expert knapper (Bruce Bradley). This cascading effect of social learning
388 might explain why there is a shared mental template between the expert group and the novice
389 group after training.

390 The negative correlation between the PC1 and PC2 values revealed a hidden structural constraint
391 regarding the relationship between cross-sectional thinning and the imposed form. Our results
392 (**Figure 5**) suggested thinner handaxes (low PC1 value) are generally more pointed/less ovate (high
393 PC2 value), which was first reported in Crompton and Gowlett's (1993) pioneering study on the
394 allometry of Kilombe handaxes. In the thinning phase of handaxe making, a knapper must strike
395 flakes that travel more than one half way across the surface while not breaking the handaxe into
396 half (1979: 90). As a corollary, we speculate that it would be easier to perform thinning if the plan
397 shape of a handaxe is narrower and more pointed, echoing the high technological difficulty of
398 making large yet thin bifacial points as perceived by American hobbyist flintknappers (Whittaker,
399 2004: 180-182). It is possible that such constraints help to explain why our novice knappers on
400 average produced more handaxes in similar shapes to those preferred by modern expert knappers,
401 however, this clearly does not explain the design target at Boxgrove. Given the ovate forms of the
402 Boxgrove assemblage, it thus requires a high skill level to overcome this structural constraint to
403 produce thin yet wide handaxes as demonstrated by the Boxgrove knappers. This also provides
404 an alternative explanation to the social transmission of form for the experimental convergence
405 on pointed forms. In this comparative context, it would only be the Boxgrove assemblage that
406 provided evidence of social conformity on a more difficult target shape.

407 In terms of our second research question, this study shows that training does have an immediate
408 intervention effect (pre-training vs. post-training) in both PC1 (skill level) and PC2 (mental tem-
409 plate). Nonetheless, once the training has been initiated, its effects across different assessments
410 on both dimensions are rather non-significant. When the performance of experts is used as a
411 reference point here, we can see that for PC2 no significance difference is detected between early
412 training, late training, and expert group, while for PC1 the expert group is clearly different from
413 the training groups, supporting our hypothesis in terms of the differential cultural reproduction
414 of mental templates and skill level. This finding provides a parallel line of evidence that corrob-
415 orates what has been suggested in Pargeter et al. (2019) that 90 hours of training for handaxe

making is still not enough for novices to reach the skill level as reflected in expert knappers, even considering the massive social support involved in the experiment set up including the direct and deliberate pedagogy and the simplified raw material procurement and preparation procedures. Methodologically speaking, this study also demonstrated that the pattern revealed by the multivariate analysis of morphometric data can nicely match with the expert knapper's 5 point grading scale of novices' knapping performances that takes multiple factors into consideration, including outcome, perceptual motor execution, and strategic understanding (See Table 2 of 2019 for more details).

Moreover, this follow-up project further adds the samples produced by the Late Acheulean toolmaker as a new benchmark to deepen our understanding of this issue. As previously shown in Key's (2019) previous finding regarding Boxgrove, it is noteworthy how constrained the range of Boxgrove assemblage morphological variation is as measured by both PC1 and PC2 even when compared with the modern expert group (Figure 4), especially given the fact that it has the largest sample size among all studied groups. Some potential explanations for this phenomenon include 1) the strong idiosyncrasy of individual expert knappers shaped by their own unique learning and practice experience; 2) the present-day skill shortage of our expert knapper as compared with Boxgrove knappers despite their multiple years of knapping practice (Milks, 2019); and/or 3) modern knappers' skill level was affected by time constraints when they were requested to produce the reference collections (Lewis et al., 2022; Schillinger et al., 2014b).

The pre-training group is unexpectedly similar to the Boxgrove group in PC2 because these novices lack the ability to effectively reduce the nodules, which are typically flat pre-prepared cortical flakes, to the desired form (Figure 9). If the given nodules already possess an oval morphology like those presented in the Boxgrove assemblage, it is likely the form of end products knapped by novices in the pre-training group will remain roughly unchanged (Winton, 2005: 113). This explanation is also supported by the comparison of average delta weight, defined as the difference between the weight of handaxe and the weight of nodule, among four groups, where the pre-training group displays the lowest value (Figure 8). It might be worth noting that the expert group is highly variable probably due to raw material starting size/shape. Achieve handaxe forms while removing as little mass as possible (i.e. making as big a handaxe as possible from the nodule) generally requires a higher skill level due to the reductive or subtractive nature of stone knapping, where correcting an error or any thinning procedure always requires the removal

447 of raw material and thereby reducing the size of a given handaxe ([Schillinger et al., 2014a](#): 130;
448 [Deetz, 1967](#): 48-49). On the other hand, the refitting analyses of the Boxgrove handaxe assemblage
449 have suggested that the nodules exploited by knappers inhabiting this site are somewhat bulky
450 and amorphous ([Roberts & Parfitt, 1998](#): 339, 360). These characteristics have been clearly
451 displayed in a recent attempt of slow-motion refitting of a handaxe specimen from Boxgrove
452 GTP17 (<https://www.youtube.com/watch?v=iS58MUJ1ZEo>). As such, we infer that behind
453 the resemblance of the pre-training group and the Boxgrove assemblage in PC2 are two types of
454 mechanisms that are fundamentally different from each other, where the latter group exhibits
455 a complex suite of cognitive and motor execution processes to transform the shapeless raw
456 materials to a delicate end product in a given shape.



Figure 9: Core 63 before (left) and after knapping(right), showing the minimal morphological change during the knapping process.

457 Although we are not the first research team to use secondary archaeological data (e.g., [Key, 2019](#)),
458 we would still like to highlight here that this research project further exemplifies the potential
459 of reusing old archaeological data in digital format to address novel research questions. In this
460 paper, the main source of archaeological data is a collection of photos produced and curated
461 more than 10 years ago, and the morphological variation data of the experimental collection are
462 also derived from photographs instead of remeasurements of the original artifacts. Given the
463 irreversible nature of archaeological excavations, digitized data, be it text, pictures, or videos,

often become the sole evidence that is available for certain research questions. Yet, it has been widely acknowledged that the reuse of archaeological data has not received enough attention among researchers in our discipline (Faniel et al., 2018; Huggett, 2018; Moody et al., 2021). Among many reasons preventing archaeologists from reusing published and digitized data (Sobotkova, 2018), the lack of a standardized practice of and motivation for data sharing is a prominent one (Marwick & Birch, 2018). As stated in the method section, we addressed this issue by sharing the raw data and the code for generating the derived data on an open-access repository. Another major and legitimate concern of archaeological data reuse is their quality. In terms of this aspect, we do acknowledge the limitations of relying on photos when it comes to the more detailed technological analysis of stone artifacts, however, our paper shows that finding the appropriate research questions given the data available is key to revealing new novel insights into the studied topic. Moreover, we believe that this type of research has a strong contemporary relevance due to the continued influence of the COVID-19 on fieldwork-related travel and direct access to archaeological artifacts (Balandier et al., 2022; Ogundiran, 2021).

5 Conclusions

Regarding the two research questions we proposed in the beginning, our case study suggested that 1) we can delineate the effects of skill level and mental template through the multivariate analysis of morphometric data, where the former is associated with cross-sectional thinning while the latter is reflected in elongation and pointedness; 2) On average training has an immediate effect of making novices to better understand the shared design targets, but 90 hours of training is still not enough for novice to reach the level of expertise as reflected in modern experienced knappers, let alone the Boxgrove tool makers, which supports our differential cultural reproduction hypothesis. At a larger theoretical level it questions the distinction between social learning of design targets vs. individual learning of the skills needed to achieve them. Traditionally archaeological experiments speaking to the literature of cultural evolution tend to use handaxe as a model artifact and focus on how copying errors emerge during the transmission of a fixed and static target using transmission chain design and alternative raw materials such as foam (Schillinger et al., 2014b, 2017, 2015). This line of inquiry is generally characterized by high internal validity (causal mechanisms) but low external validity (generalizability to archaeological data). In contrast, our study unpacks the differential reproductions of two major sources of variation and reveals how

494 the development of motor skill during learning is constraining the achievement of the socially
495 learnt design target, through an actualistic experimental setting featuring a higher degree of
496 external validity ([Liu & Stout, 2022](#)). In the future, more robust experimental studies are needed
497 to deepen our understanding of the relationship between skill acquisition and the morphological
498 variability of handaxes in the proper developmental context ([Högberg, 2018](#); [Lew-Levy et al., 2020](#);
499 [Nowell, 2021](#)) as well as their implications for the biological and cultural evolution of the hominin
500 lineages.

501 **6 CRediT authorship contribution statement**

502 **Cheng Liu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology,
503 Visualization, Writing – original draft, Writing – review & editing. **Nada Khreisheh:** Investigation,
504 Writing – review & editing. **Dietrich Stout:** Conceptualization, Investigation, Resources, Funding
505 acquisition, Supervision, Writing – original draft, Writing – review & editing. **Justin Pargeter:**
506 Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing –
507 review & editing.

508 **7 Declaration of competing interest**

509 The authors declare that they have no known competing financial interests or personal relation-
510 ships that could have appeared to influence the work reported in this paper.

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