

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

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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. Here we present results from  
11     a multidisciplinary study of Late Acheulean handaxe-making skill acquisition involving thirty  
12     naïve participants trained for up to 90 hours in Late Acheulean style handaxe production and  
13     three expert knappers. We compare their handaxe to the Late Acheulean handaxe assemblage  
14     from Boxgrove, UK. Through the principal component analysis of morphometric data derived  
15     from images, our study suggested that knapper skill levels and mental templates have a  
16     relatively clear manifestation in different aspects of handaxe morphology. The former relates  
17     to cross-sectional thinning (PC1), while the latter refers to handaxe elongation and pointedness  
18     (PC2). Moreover, we also evaluated the effects of training using the data from a 90-hour-long  
19     knapping skill acquisition experiment. We found that reaching the skill level of modern experts  
20     requires more training time than was permitted in this extensive and long-running training  
21     program. ¶

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

24      **Contents**

25 <b>1 Introduction</b>	2
26 <b>2 Materials and methods</b>	6
27         2.1 Boxgrove handaxe collection . . . . .	6
28         2.2 Experimental handaxe collection . . . . .	8
29         2.3 Lithic analysis . . . . .	9
30         2.4 Statistical analyses . . . . .	10

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<b>31</b>	<b>3 Results</b>	<b>11</b>
32	3.1 Principal component analysis . . . . .	11
33	3.2 Effects of training . . . . .	15
<b>34</b>	<b>4 Discussion</b>	<b>17</b>
<b>35</b>	<b>5 Conclusions</b>	<b>22</b>
<b>36</b>	<b>6 CRediT authorship contribution statement</b>	<b>23</b>
<b>37</b>	<b>7 Declaration of competing interest</b>	<b>23</b>
<b>38</b>	<b>8 Acknowledgements</b>	<b>23</b>
<b>39</b>	<b>References</b>	<b>23</b>

## **40 1 Introduction**

41 The morphological variability of Acheulean handaxes has been one of the most well-studied  
 42 and well-published topics in paleolithic archaeology (Key & Lycett, 2019; Petraglia & Korisettar,  
 43 1998; White, 1998). Despite the recurrent narrative emphasizing the homogeneity and longevity  
 44 of handaxe assemblages on a global scale and the conservatism behind this phenomenon that  
 45 evokes genetic explanations (Corbey et al., 2016; Corbey, 2020; Richerson & Boyd, 2005; Sterelny,  
 46 2004), many researchers have recognized the diversity within what has been deemed as a unified  
 47 Acheulean “tradition” and tried to dissect the sources and meaning of this variation (Lycett &  
 48 Gowlett, 2008; Nowell, 2002; Nowell & White, 2010; Sharon et al., 2011). More specifically, a  
 49 complex suite of interconnecting factors (Lycett & Cramon-Taubadel, 2015) have been identified  
 50 to contribute to handaxe morphological variation, including but not limited to raw material  
 51 variability (Eren et al., 2014; Lycett et al., 2016; McNabb & Cole, 2015; Sharon, 2008), percussor  
 52 properties (Shipton et al., 2009), functional differences (Key et al., 2016; Key & Lycett, 2017; Lycett  
 53 & Gowlett, 2008; Machin et al., 2007; White & Foulds, 2018), reduction method/intensity (Shipton  
 54 et al., 2009; Shipton & Clarkson, 2015), time budgets (Schillinger et al., 2014b), learning processes  
 55 (Kempe et al., 2012; Lycett et al., 2016), social signaling (Kohn & Mithen, 1999; Spikins, 2012),  
 56 aesthetic preferences (Gowlett, 2021; Le Tensorer, 2006), knapper skill levels (Caruana & Herries,  
 57 2021; Herzlinger et al., 2017; Stout et al., 2014), and mental templates (García-Medrano et al., 2019;  
 58 Hutchence & Scott, 2021; Schillinger et al., 2017). From this extensive list, knapper skill levels and  
 59 mental templates have been repeatedly mentioned and discussed in the now extensive corpus

60 of handaxe studies, and Boxgrove handaxes have been one of the most studied assemblages  
61 from these two angles. Of particular attention here are the experimental works conducted by  
62 Stout et al. (2014) focusing on inferring knapping skill level and Garcia-Medrano et al. (2019)  
63 identifying the mental template of the Boxgrove assemblage. Our paper combines these two  
64 perspectives and provides novel insights to the same archaeological assemblage by comparing it  
65 with experimentally made handaxes.

66 In its classical definition, the term mental template indicates that the “idea of the proper form  
67 of an object exists in the mind of the maker, and when this idea is expressed in tangible form in  
68 raw material, an artifact results” (Deetz, 1967: 45). This concept lies at the very foundation of the  
69 cultural-historical approach in that the identification of archaeological cultures is based on the  
70 existence of distinct mental templates in a given spatial-temporal framework. Early researchers,  
71 whether explicitly or implicitly, often endorsed this conceptual framework and actively applied it  
72 in the typological analysis of handaxes at the regional level (Roe, 1969; Wenban-Smith et al., 2000;  
73 Wenban-Smith, 2004). Combined with the production of large flakes, the emergence of mental  
74 templates (or “imposed form”) has been recognized as a major technological innovation of the  
75 Acheulean compared with the Oldowan (Isaac, 1986). For a decade or so, this concept has been  
76 less frequently used, since it was criticized for a) its normative and static assumption (Lyman  
77 & O’Brien, 2004), b) ignoring other competing factors such as raw material constraints (White,  
78 1995), and c) being constrained by the basic fracture mechanics and design space of bifacial  
79 technology (Moore, 2011; Moore & Perston, 2016). To avoid the historical baggage associated  
80 with this controversial term, some researchers developed alternative frameworks such as “design  
81 imperatives” derived from utilitarian and ergonomic principles, which refers to a set of minimum  
82 features shared by all handaxes including their glob-but, forward extension, support for the  
83 working edge, lateral extension, thickness adjustment, and skewness (Gowlett, 2006; Wynn &  
84 Gowlett, 2018). The major difference between the concepts of design imperatives and mental  
85 templates lies in the fact that the former does not necessarily require the presence of explicit  
86 internal representations of form, where the shape of handaxes can instead emerge “through the  
87 coalescence of ergonomic needs in the manipulation of large cutting tools (Wynn, 2021: 185).”  
88 Recently, researchers have actively addressed the above-mentioned critiques and reconcep-  
89 tualized the concept of mental template in the study of handaxe morphology. Regarding the  
90 normative and static assumptions, Hutchence and Scott (2021), for example, leveraged the theory

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

111 Following the reconceptualization of the mental template as a more flexible and interactive  
112 concept, one possible way of defining skill is the capacity for a knapper to realize mental templates  
113 using the resources available (Roux et al., 1995: 66). This version of conceptualization, particularly  
114 relevant when it comes to motor skills such as knapping, can be dismantled into two mutually  
115 dependent aspects, namely the intentional aspect (goal/strategic planning) and the operational  
116 aspect (means/motor execution) (Connolly & Dalgleish, 1989). It also roughly corresponds  
117 to the well-known dichotomy developed by French lithic analysts of “*connaissance*” (abstract  
118 knowledge) and “*savoir-faire*” (practical know-how) (Pelegrin, 1993). As Stout (2002: 694) noted,  
119 the acquisition of skill is deeply rooted in its social context, and it is not composed of “some  
120 rigid motor formula” but “how to act in order to solve a problem”. This ecological notion of skill  
121 somewhat mirrors Hutchence and Scott’s (2021) reconceptualization of the mental template  
122 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).

Drawing on these two lines of literature, we aim to explore the possibility of dissecting the interaction of skill level and mental template through a comparative study of an archaeological handaxe assemblage known for its remarkable high skill level, a reference handaxe collection produced by modern knapping experts, and an experimental handaxe sample produced by modern novice knappers. We generated the novice handaxe collection from a 90-hour skill acquisition experiment providing the opportunity to introduce the diachronic dimension of training time and interrogate its impact on the variables of interest. As such, we propose the following two interconnected research questions in this article: 1) Can skill level and mental templates be efficiently detected from handaxe morphometric data? Accordingly, we hypothesize that the morphometric variables showing overlap between Boxgrove and expert samples while being markedly different from novice samples reflect skill level differences, and all three group should show a similar mental template since this is the common target. 2) How does training affect novices' performance in these two aspects? Our hypothesis is that throughout the training the novice samples should become more similar to expert samples in both skill level and mental template.

153 **2 Materials and methods**

154 **2.1 Boxgrove handaxe collection**

155 The archaeological site of Boxgrove is located in the former Eartham quarry, Boxgrove, West Sussex,  
156 featuring a long sequence of Middle Pleistocene deposits (Pope et al., 2020; Roberts & Parfitt,  
157 1998). This 500-ka-old site has documented exceedingly rich details of Lower Paleolithic hominin  
158 subsistence behaviors (Smith, 2013, 2012) and their paleoenvironmental contexts (Holmes et  
159 al., 2010). In addition to the presence of one of the earliest hominin fossil (tentatively assigned  
160 to *Homo heidelbergensis*, Hillson et al., 2010; Lockey et al., 2022) and bone assemblages with  
161 anthropogenic modifications in northern Europe (Bello et al., 2009), Boxgrove is mostly known  
162 for its large sample size of Late Acheulean-style flint handaxes and the high skill level reflected  
163 in their manufacture (Figure 1). As such, it has received wide research attention in the past two  
164 decades regarding the relationships between technology, cognition, and skills (García-Medrano et  
165 al., 2019; Iovita et al., 2017; Iovita & McPherron, 2011; Key, 2019; Shipton & Clarkson, 2015; Stout  
166 et al., 2014). To identify the morphological manifestation of knappers' skill level in our study, we  
167 selected a complete handaxe assemblage (n=326) previously analyzed and reported in digital  
168 formats by Iovita and McPherron (2011), which is currently curated at the Franks House of the  
169 British Museum (Iovita et al., 2017). The digital photographs are taken of each handaxe at a 90°  
170 angle, which was oriented with the tip to the right of the photos, and the camera faces the most  
171 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.

172 **2.2 Experimental handaxe collection**

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

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

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

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

### 216 **2.3 Lithic analysis**

217 To better understand the morphological variation of Boxgrove handaxe collection, we adopted a  
218 standardized analytical procedure to extract the morphometric information from 752 photos of  
219 the studied samples ([Iovita & McPherron, 2011](#)), which include both the front and lateral views  
220 of a given specimen. First, we used Adobe Photoshop to conduct a batch transformation of  
221 the samples' pixel scale into a real-world measurement scale based on the fixed photographic  
222 setting. This is then followed by the batch conversion of color photographs to a black-and-white  
223 binary format. Subsequently, we cropped the silhouettes of handaxes one by one using the  
224 Quick Selection Tool in Adobe Photoshop. The metric measurements were conducted in ImageJ  
225 ([Rueden et al., 2017](#)), where we employed a custom ImageJ script ([Pargeter et al., 2019](#)) to mea-  
226 sure the maximum length, width, and thickness of a given silhouette. The width and thickness  
227 measurements are taken at 10% increments of length starting at the tip of each handaxe (**Figure**  
228 [2](#)), which eventually leads to 19 morphometric variables in total (1 length measurement, 9 width  
229 measurements, and 9 thickness measurements). Finally, we calculated the geometric means of all  
230 19 linear measurements to create a scale-free data set that preserves the individual morphological  
231 variation at the same time ([Lycett et al., 2006](#)). This allometric scaling procedure controls for size  
232 variation which may come from initial blanks and/or reduction intensity (shaping/resharpening).

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

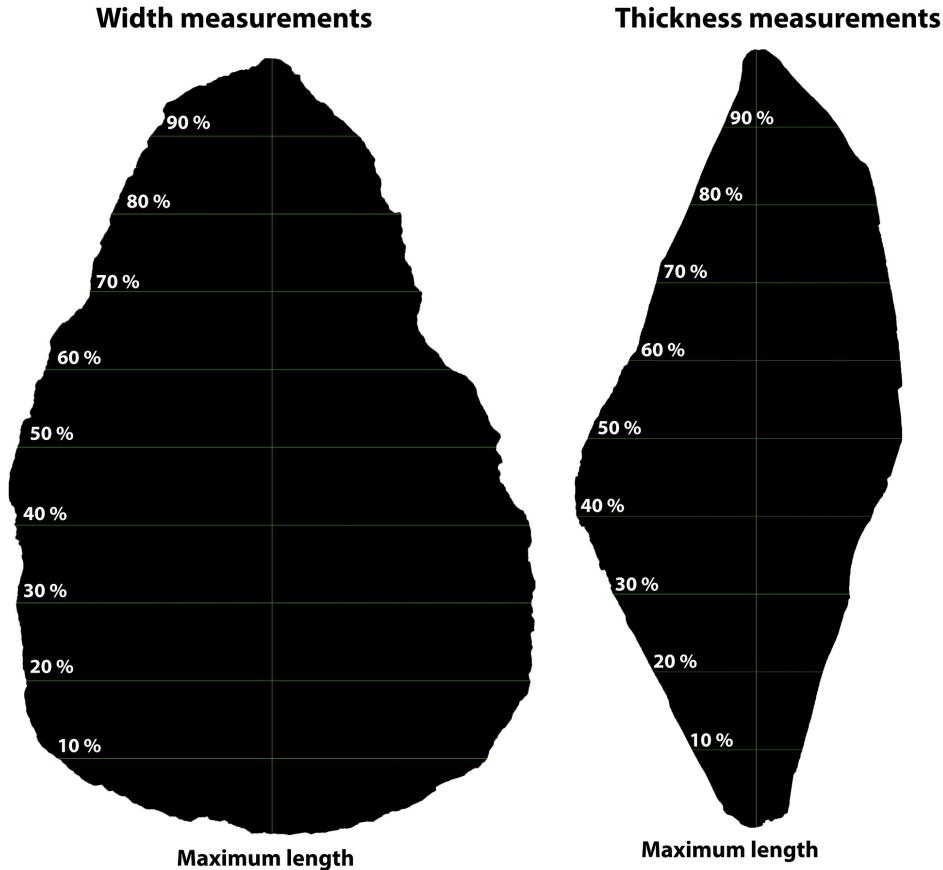


Figure 2: A visual demonstration of the handaxe measurement protocol using Image J (after Pargeter et al. 2019: Figure 5).

## 237 **2.4 Statistical analyses**

238 We use the statistical programming language R 4.1.1 (R Core Team, 2021) to conduct statistical  
239 analyses and data visualization in this study, particularly the R packages “FactoMineR” (Lê et  
240 al., 2008) and “ggstatsplot” (Patil, 2021). As the initial step, simple visualization techniques such  
241 scatter plots are frequently used to explore the relationships between variables of interest. Given  
242 the number of variables involved in this study, we used principal component analysis (PCA) to  
243 reduce the dimension and identify the possible patterns in this morphometric data set, which  
244 is one of the most used techniques in similar studies (García-Medrano, Maldonado-Garrido, et  
245 al., 2020; García-Medrano, Ashton, et al., 2020; Herzlinger et al., 2017; Iovita & McPherron, 2011;

246 Shipton & Clarkson, 2015; Stout et al., 2014). To detect the effect of training on novices' perfor-  
247 mance as compared with archaeological samples and handaxe made by experts, we also compare  
248 the corresponding metrics built on PCA across different training periods and across all groups  
249 using the Games-Howell nonparametric post-hoc test. Compared with other nonparametric tests  
250 frequently used in archaeological research for multiple group comparison such as Tukey's test,  
251 Games-Howell test does not rely on the assumptions of sample normality, and equal sample sizes  
252 and equal variance are not necessary conditions to perform this test. The sample size of each  
253 compared group can be as low as 6 (Games & Howell, 1976; Sauder & DeMars, 2019). Lastly, we  
254 compare the delta weight, as defined by the difference between initial nodule weight and end  
255 product weight, between these groups to understand the effect of training on reduction intensity.  
256 This study adheres to the principles of reproducibility and data transparency of archaeological  
257 research by depositing all the codes and data sets involved in an open-access online repository  
258 (Marwick, 2017), which are available as supplementary materials and can be accessed through  
259 the author's Github (<https://github.com/Raylc/Boxgrove-Exp>).

## 260 3 Results

### 261 3.1 Principal component analysis

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

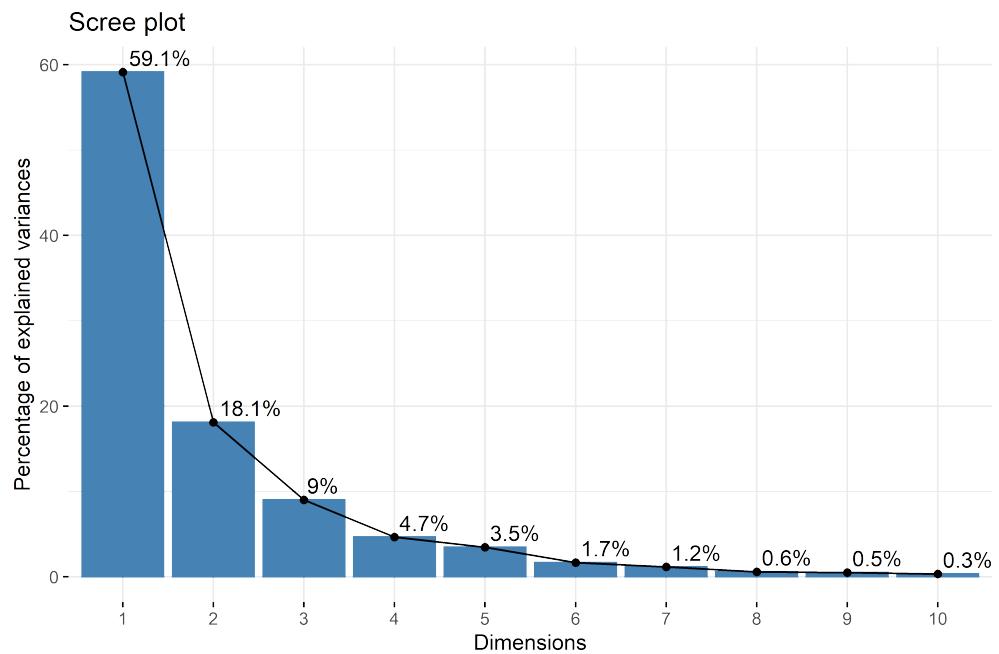


Figure 3: A scree plot showing the percentage of explained variances of the first 10 principal components.

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.

<b>Variables</b>	<b>Dim.1</b>	<b>Dim.2</b>
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

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

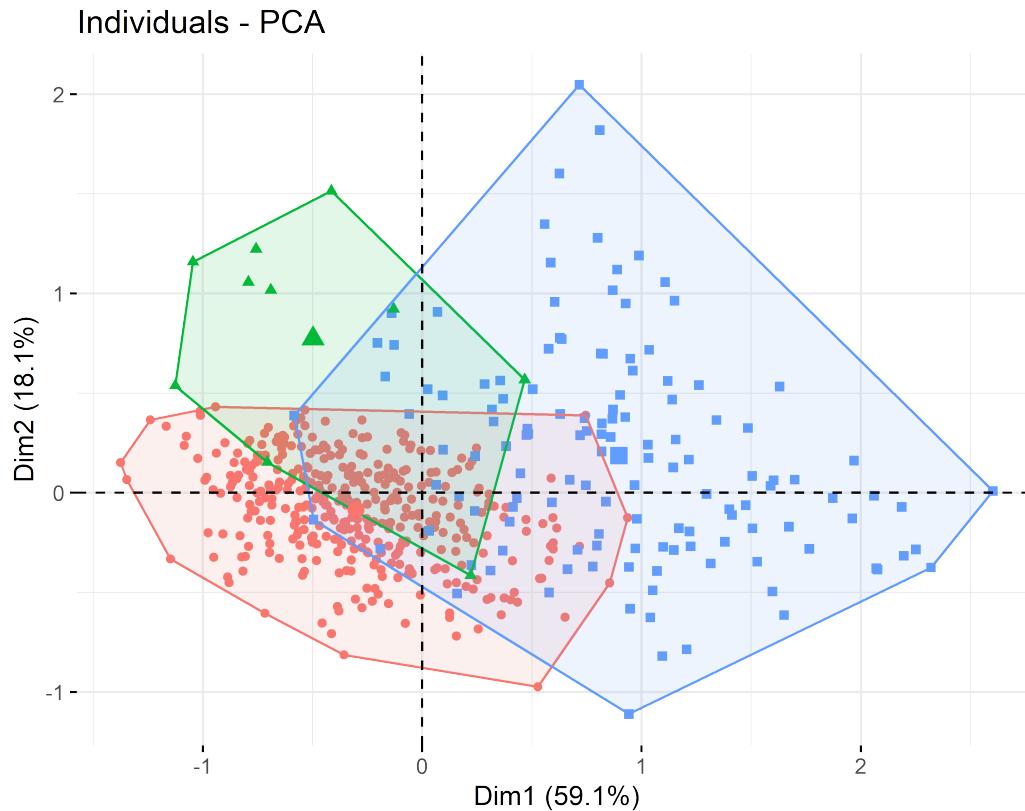


Figure 4: A principal component scatter plot of handaxes from the groups of Boxgrove (red, n=326), expert (green, n=10), and novice (blue, n=132).

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

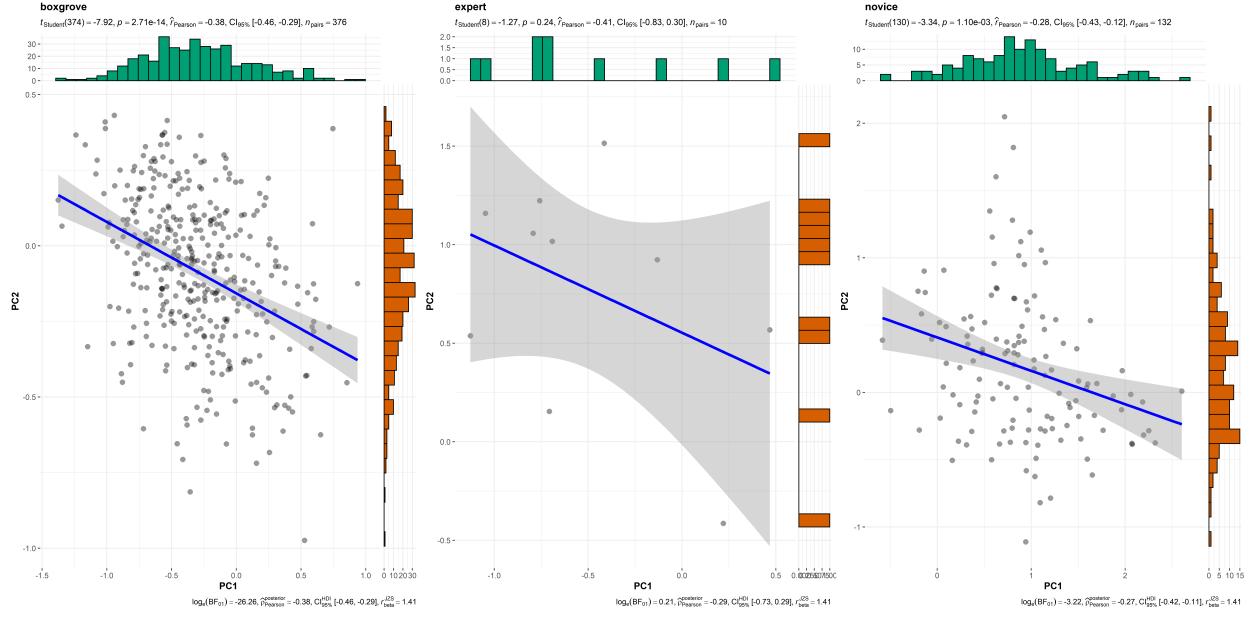


Figure 5: A scatter plot showing the correlation between PC1 and PC2 respectively in the groups of Boxgrove (left,  $n=326$ ), expert (middle,  $n=10$ ), and novice (right,  $n=132$ ). The upper left area in each individual plot displays statistical reporting from a frequentist perspective, including 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.

### 286 3.2 Effects of training

287 We extracted the PC1 and PC2 values of individual handaxes and compared them between  
 288 different groups, where the novice group was divided into three sub-groups based on their  
 289 training stages as specified in the method section. As such, we found that for PC1 values (**Figure**  
 290 **6**), the only two group comparisons that are **not** statistically significant are the one between  
 291 Boxgrove and Expert ( $t = -1.65, p > 0.05$ ) and the one between Early training and Late training  
 292 stages ( $t = -0.649, p > 0.05$ ), which at least partially confirms our visual observation of the  
 293 general PCA scatter plot. Likewise, for PC2 values (**Figure 7**), the group comparison between  
 294 the Early training and Late stages again is not statistically significant ( $t = 0.333, p > 0.05$ ). An  
 295 unexpected result is that the mean PC2 value difference between the Pre-training group and  
 296 Boxgrove is also not statistically significant ( $t = -0.818, p > 0.05$ ). These results essentially  
 297 suggest that there is a significant difference between the pre-training group and post-training  
 298 groups in both PC1 (thinning) and PC2 (pointedness). However, the effects of training across  
 299 different assessment periods on both dimensions are not significant. Regarding the delta weight  
 300 of different groups, our analysis (**Figure 8**) suggests that there is a significant difference between  
 301 the pre-training group and Late training group, while all other pairwise group comparison results

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

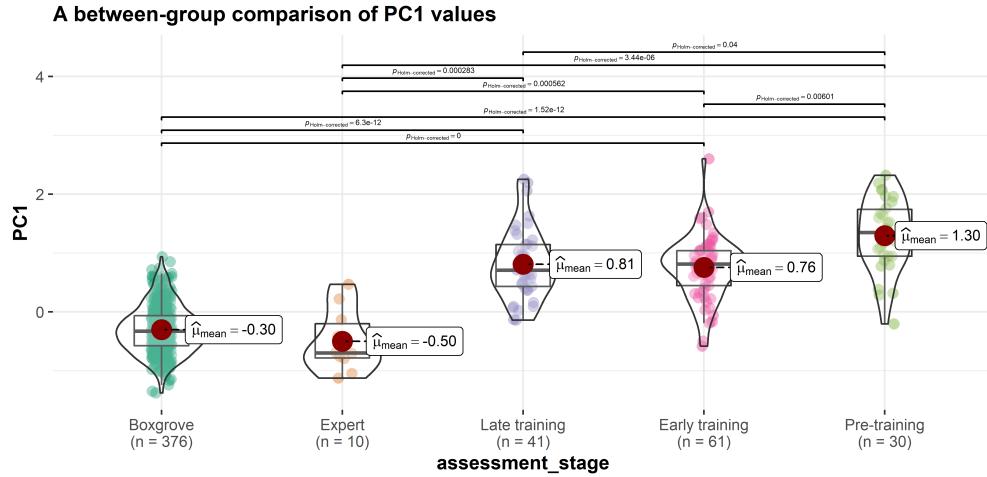


Figure 6: A between-group comparison of PC1 values.

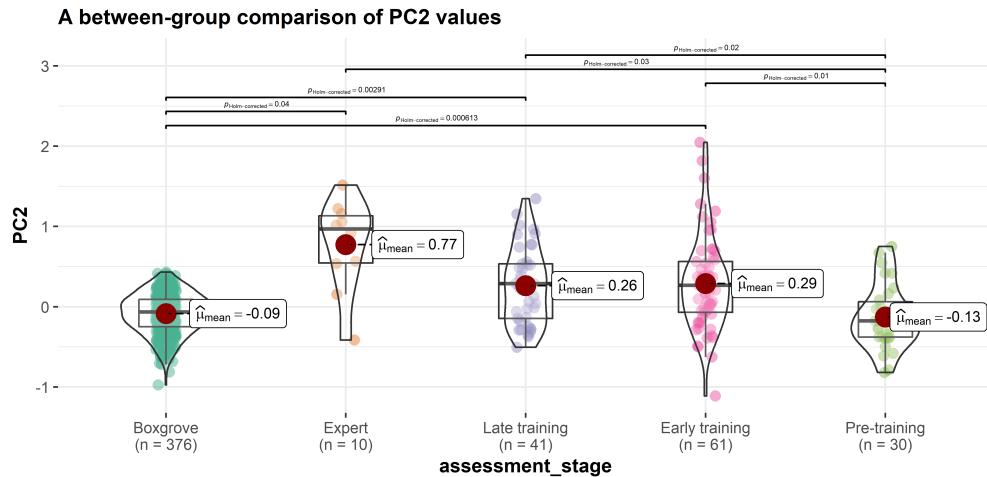


Figure 7: A between-group comparison of PC2 values.

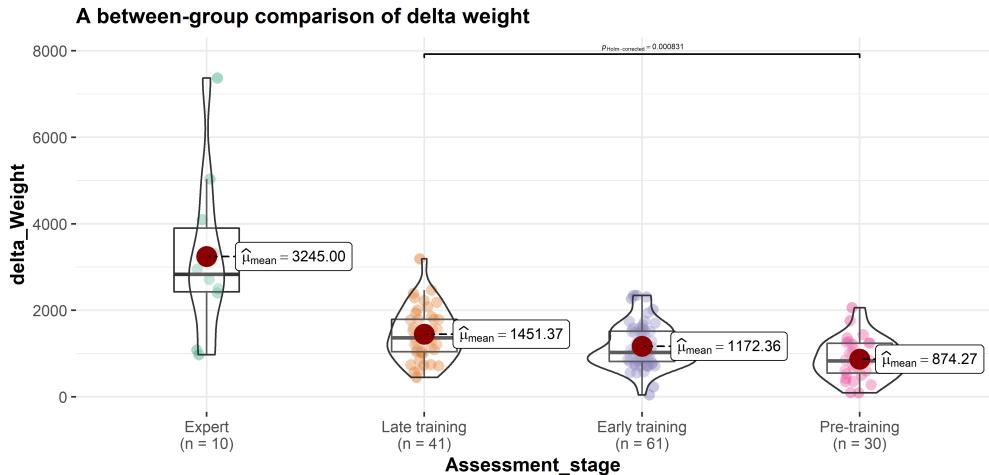


Figure 8: A comparison of the delta weight between the pre-training, early training, late training, and the expert group.

## 304 4 Discussion

305 Our study suggests that both skill level and mental template have a relatively clear manifestation in  
 306 different aspects of handaxe morphology, where the former is related to cross-sectional thinning  
 307 (PC1) while the latter relates to handaxe elongation and pointedness (PC2). Moreover, we also  
 308 evaluated the effects of training using the data from a 90-hour long knapping skill acquisition  
 309 experiment and confirmed the previous finding (2019) that reaching the skill level of modern  
 310 experts requires more training time than was permitted in this extensive and long-running  
 311 training program. In accordance with the existing literature on handaxe knapping skill (Callahan,  
 312 1979; Caruana, 2020; Stout et al., 2014), the results of PCA suggested that PC1 (cross-sectional  
 313 thinning) is a robust indicator of skill level as it is a common feature shared by modern expert  
 314 knapper and Boxgrove knappers. Thinning is regarded as a technique requiring a high knapping  
 315 skill level because it requires one to carefully detach flakes in an invasive manner while not  
 316 breaking the handaxe into several pieces, serving the purpose of achieving the desired convexity  
 317 and/or volume. This procedure involves precise control of striking forces, strategic choice of  
 318 platform external angle, and attentive preparation of bifacial intersection plane, all of which  
 319 were part of our experimental training program (Callahan, 1979; Caruana, 2022; Pargeter et  
 320 al., 2020; Shipton et al., 2013; Stout et al., 2014). Experimental studies have also shown that  
 321 the thinning stage of handaxe produce often involves the use of soft hammers, which is also  
 322 supported by indirect archaeological evidence of flake attributes from Boxgrove (Roberts & Parfitt,

323 1998: 384-394; [Roberts & Pope, 2009](#)), although the validity of differentiating purcussor types  
324 (hard hammerstone, soft hammerstone, and antler hammer) based on flake attributes has been  
325 challenged by other experimental studies([Driscoll & García-Rojas, 2014](#)). It should be noted that  
326 both our experts and novices frequently used soft hammers in the production of experimental  
327 assemblages. In the skill acquisition experiments, novice knappers were explicitly taught to  
328 switch to the soft hammer for thinning purposes, but some of them did not follow the instruction  
329 during the assessment. On the other hand, it has also been shown that hard hammers can also  
330 be used to achieve similar thinning results ([Bradley & Sampson, 1986](#); [Pelcin, 1997](#)), and the  
331 replicas produced by Bruce Bradley in our expert reference collection did not involve the use of  
332 soft hammers.

333 Given the dissimilarity of PC2 (elongation and pointedness) values between archaeological and  
334 experimental samples and its similarity among modern knappers, we argue that this dimension  
335 reflects different mental templates, where the Boxgrove assemblage displays an ovate shape  
336 featuring a wider tip while the experimental assemblages are characterized by a more pointed  
337 shape with a longer central axis. Our results regarding the ovate plan morphology of the Boxgrove  
338 assemblage generally supports what have been reported by Shipton and White ([2020](#)) as well as  
339 Garcia-Medrano et al. ([2019](#)). The finding that the expert group has a mental template different  
340 from the Boxgrove assemblage is rather surprising since they were requested to mimic Boxgrove  
341 handaxes, a potential reason of which could be that these expert didn't have Boxgrove handaxes at  
342 hand as model during the manufacture and thus followed their vague memory of a "representative  
343 teardrop Late Acheulean handaxe." In general, this pattern may reflect a divergence of group-level  
344 aesthetic choices as expected under the theoretical framework of the communities of practice  
345 ([Wenger, 1998](#)), which could potentially provide an mechanistic explanation to some macro-  
346 level cultural phenomena such as regionalization ([Ashton & Davis, 2021](#); [Davis & Ashton, 2019](#);  
347 [García-Medrano et al., 2022](#); [Shipton & White, 2020](#)). The most common form of learning in  
348 the experiment occurred in the group condition, where the instructor, as the competent group  
349 member, directed the joint enterprise through actively teaching multiple novices at the same time.  
350 Meanwhile, novices had the chance to also communicate and learn from their peers, producing a  
351 shared repertoire of artifacts and actions. Unfortunately, the handaxe data from the instructor (N.  
352 Khreisheh) are unavailable, but it should be noted that the instructor has learned how to knap  
353 and how to teach knapping from one of our expert knapper (Bruce Bradley). This cascading effect  
354 of social learning might explain why there is a shared mental template between the expert group

355 and the novice group after training.

356 The negative correlation between the PC1 and PC2 values revealed a hidden structural constraint  
357 regarding the relationship between cross-sectional thinning and the imposed form. Our results  
358 (**Figure 5**) suggested thinner handaxes (low PC1 value) are generally more pointed/less ovate (high  
359 PC2 value), which was first reported in Crompton and Gowlett's (1993) pioneering study on the  
360 allometry of Kilombe handaxes. In the thinning phase of handaxe making, a knapper must strike  
361 flakes that travel more than one half way across the surface while not breaking the handaxe into  
362 half (1979: 90). As a corollary, we speculate that it would be easier to perform thinning if the plan  
363 shape of a handaxe is narrower and more pointed, echoing the high technological difficulty of  
364 making large yet thin bifacial points as perceived by American hobbyist flintknappers (Whittaker,  
365 2004: 180-182). It is possible that such constraints help to explain why our novice knappers on  
366 average produced more handaxes in similar shapes to those preferred by modern expert knappers,  
367 however, this clearly does not explain the design target at Boxgrove. Given the ovate forms of the  
368 Boxgrove assemblage, it thus requires a high skill level to overcome this structural constraint to  
369 produce thin yet wide handaxes as demonstrated by the Boxgrove knappers. This also provides  
370 an alternative explanation to the social transmission of form for the experimental convergence  
371 on pointed forms. In this comparative context, it would only be the Boxgrove assemblage that  
372 provided evidence of social conformity on a more difficult target shape.

373 In terms of our second research question, this study shows that training does have an immediate  
374 intervention effect (pre-training vs. post-training) in both PC1 (skill level) and PC2 (mental tem-  
375 plate). Nonetheless, once the training has been initiated, its effects across different assessments  
376 on both dimensions are rather non-significant. This finding provides a parallel line of evidence  
377 that corroborates what has been suggested in Pargeter et al. (2019) that 90 hours of training for  
378 handaxe making is still not enough for novices to reach the skill level as reflected in expert knap-  
379 pers, even considering the massive social support involved in the experiment set up including  
380 the direct and deliberate pedagogy and the simplified raw material procurement and preparation  
381 procedures. Methodologically speaking, this study also demonstrated that the pattern revealed by  
382 the multivariate analysis of morphometric data can nicely match with the expert knapper's 5 point  
383 grading scale of novices' knapping performances that takes multiple factors into consideration,  
384 including outcome, perceptual motor execution, and strategic understanding (See Table 2 of 2019  
385 for more details).

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

397 The pre-training group is unexpectedly similar to the Boxgrove group in PC2 because these  
398 novices lack the ability to effectively reduce the nodules, which are typically flat pre-prepared  
399 cortical flakes, to the desired form (Figure 9). If the given nodules already possess an oval  
400 morphology like those presented in the Boxgrove assemblage, it is likely the form of end products  
401 knapped by novices in the pre-training group will remain roughly unchanged (Winton, 2005: 113).  
402 This explanation is also supported by the comparison of average delta weight, defined as the  
403 difference between the weight of handaxe and the weight of nodule, among four groups, where  
404 the pre-training group displays the lowest value (Figure 8). It might be worth noting that the  
405 expert group is highly variable probably due to raw material starting size/shape. Achieve handaxe  
406 forms while removing as little mass as possible (i.e. making as big a handaxe as possible from  
407 the nodule) generally requires a higher skill level due to the reductive or subtractive nature of  
408 stone knapping, where correcting an error or any thinning procedure always requires the removal  
409 of raw material and thereby reducing the size of a given handaxe (Schillinger et al., 2014a: 130;  
410 Deetz, 1967: 48-49). On the other hand, the refitting analyses of the Boxgrove handaxe assemblage  
411 have suggested that the nodules exploited by knappers inhabiting this site are somewhat bulky  
412 and amorphous (Roberts & Parfitt, 1998: 339, 360). These characteristics have been clearly  
413 displayed in a recent attempt of slow-motion refitting of a handaxe specimen from Boxgrove  
414 GTP17 (<https://www.youtube.com/watch?v=iS58MUJ1ZEo>). As such, we infer that behind  
415 the resemblance of the pre-training group and the Boxgrove assemblage in PC2 are two types of  
416 mechanisms that are fundamentally different from each other, where the latter group exhibits  
417 a complex suite of cognitive and motor execution processes to transform the shapeless raw

<sup>418</sup> 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.

<sup>419</sup> Although we are not the first research team to use secondary archaeological data (e.g., [Key, 2019](#)),  
<sup>420</sup> we would still like to highlight here that this research project further exemplifies the potential  
<sup>421</sup> of reusing old archaeological data in digital format to address novel research questions. In this  
<sup>422</sup> paper, the main source of archaeological data is a collection of photos produced and curated  
<sup>423</sup> more than 10 years ago, and the morphological variation data of the experimental collection are  
<sup>424</sup> also derived from photographs instead of remeasurements of the original artifacts. Given the  
<sup>425</sup> irreversible nature of archaeological excavations, digitized data, be it text, pictures, or videos,  
<sup>426</sup> often become the sole evidence that is available for certain research questions. Yet, it has been  
<sup>427</sup> widely acknowledged that the reuse of archaeological data has not received enough attention  
<sup>428</sup> among researchers in our discipline ([Faniel et al., 2018](#); [Huggett, 2018](#); [Moody et al., 2021](#)). Among  
<sup>429</sup> many reasons preventing archaeologists from reusing published and digitized data ([Sobotkova,](#)  
<sup>430</sup> [2018](#)), the lack of a standardized practice of and motivation for data sharing is a prominent one  
<sup>431</sup> ([Marwick & Birch, 2018](#)). As stated in the method section, we addressed this issue by sharing the  
<sup>432</sup> raw data and the code for generating the derived data on an open-access repository. Another  
<sup>433</sup> major and legitimate concern of archaeological data reuse is their quality. In terms of this aspect,  
<sup>434</sup> we do acknowledge the limitations of relying on photos when it comes to the more detailed

435 technological analysis of stone artifacts, however, our paper shows that finding the appropriate  
436 research questions given the data available is key to revealing new novel insights into the studied  
437 topic. Moreover, we believe that this type of research has a strong contemporary relevance due  
438 to the continued influence of the COVID-19 on fieldwork-related travel and direct access to  
439 archaeological artifacts (Balandier et al., 2022; Ogundiran, 2021).

## 440 5 Conclusions

441 Regarding the two research questions we proposed in the beginning, our case study suggested that  
442 1) we can delineate the effects of skill level and mental template through the multivariate analysis  
443 of morphometric data, where the former is associated with cross-sectional thinning while the  
444 latter is reflected in elongation and pointedness; 2) On average training has an immediate effect of  
445 making novices to better understand the shared design targets, but 90 hours of training is still not  
446 enough for novice to reach the level of expertise as reflected in modern experienced knappers, let  
447 alone the Boxgrove tool makers. At a larger theoretical level it questions the distinction between  
448 social learning of design targets vs. individual learning of the skills needed to achieve them. To  
449 illustrate, a thin cross section could be part of a mental template or design target and was explicitly  
450 instructed by our expert instructor to novices, but novices cannot fully understand nor achieve  
451 this technological goal due to the constraint of skill level, making it a robust indicator of the latter.  
452 Traditionally archaeological experiments speaking to the literature of cultural evolution tend to  
453 use handaxe as a model artifact and focus on how copying errors emerge during the transmission  
454 of a fixed and static target using transmission chain design and alternative raw materials such as  
455 foam (Schillinger et al., 2014b, 2017, 2015). This line of inquiry is generally characterized by high  
456 internal validity (causal mechanisms) but low external validity (generalizability to archaeological  
457 data). In contrast, our study unpacks the differential reproductions of two major sources of  
458 variation and reveals how the development of motor skill during learning is constraining the  
459 achievement of the socially learnt design target, through an actualistic experimental setting  
460 featuring a higher degree of external validity (Liu & Stout, 2022). In the future, more robust  
461 experimental studies are needed to deepen our understanding of the relationship between skill  
462 acquisition and the morphological variability of handaxes in the proper developmental context  
463 (Högberg, 2018) as well as their implications for the biological and cultural evolution of the  
464 hominin lineages.

## 465 6 CRediT authorship contribution statement

466 **Cheng Liu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology,  
467 Visualization, Writing – original draft, Writing – review & editing. **Nada Khreisheh:** Investigation,  
468 Writing – review & editing. **Dietrich Stout:** Conceptualization, Investigation, Resources, Funding  
469 acquisition, Supervision, Writing – original draft, Writing – review & editing. **Justin Pargeter:**  
470 Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing –  
471 review & editing.

## 472 7 Declaration of competing interest

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

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