

1 Dissecting the interaction between 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 production; Boxgrove; Experimental archaeology;
23 Skill level; Mental template

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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 of

60 handaxe studies, and Boxgrove handaxes have been one of the most studied assemblages from
61 these two angles. Of particular attention here are the experimental works conducted by Stout
62 et al. (2014) focusing on inferring high 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 internal
86 representation, where handaxes can emerge “through the coalescence of ergonomic needs in the
87 manipulation of large cutting tools (Wynn, 2021: 185).”

88 Until recently, researchers have actively addressed the above-mentioned critiques and recon-
89 ceptualized 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, especially how the social norms behind the consolidated material
93 expressions were developed and negotiated by individuals in a group who have a shared history of
94 learning. They further emphasized that emergent actions of individual knappers also contribute
95 greatly to the shape of Boxgrove handaxes but they were simultaneously constrained by the im-
96 position of social norms. This view also somewhat echoes the “individualized memic construct”
97 proposed by McNabb et al. (2004), which highlighted the influence of individual agency that is
98 complementary to the traditionally favored explanation of social learning. As for the critique
99 towards confounding factors explaining morphological variability, raw material is often treated
100 as an important variable to be controlled at the very beginning of a research design focusing on
101 mental templates. This is best exemplified by an experimental study of García-Medrano et al.
102 (2019), where they carefully chose experimental nodules mirroring those found in the Boxgrove
103 archaeological assemblage in composition, size, and shape. Regarding the critique of design space
104 constraint, Moore and Perston’s experiment (2016) suggested that bifaces can be manufactured
105 through flake removals dictated by a random algorithm. However, Moore (2020: 656-657) also
106 suggested that these random experiments cannot produce “attributes like the congruent symme-
107 tries of handaxes seen in the Late Acheulean.” In short, when exercised with proper caution, the
108 concept of mental templates still has its value in our study of handaxe morphological variation,
109 which can be further dissected into a series of shape variables corresponding to pointedness,
110 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) 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 al.,
159 2010). In addition to the presence of one of the earliest hominin fossil (*Homo heidelbergensis*,
160 Hillson et al., 2010) and bone assemblages with anthropogenic modifications in northern Europe
161 (Bello et al., 2009), Boxgrove is mostly known for its large sample size of Late Acheulean-style flint
162 handaxes and the high skill level reflected in their manufacture (Figure 1). As such, it has received
163 wide research attention in the past two decades regarding the relationships between technology,
164 cognition, and skills (García-Medrano et al., 2019; Iovita et al., 2017; Iovita & McPherron, 2011; Key,
165 2019; Shipton & Clarkson, 2015; Stout et al., 2014). To identify the morphological manifestation of
166 knappers' skill level in our study, we selected a complete handaxe assemblage (n=326) previously
167 analyzed and reported in digital formats by Iovita and McPherron (2011), which is currently
168 curated at the Franks House of the British Museum (Iovita et al., 2017). The digital photographs
169 are taken of each handaxe at a 90° angle, which was oriented with the tip to the right of the photos,
170 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.

171 **2.2 Experimental handaxe collection**

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

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

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

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

215 **2.3 Lithic analysis**

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

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

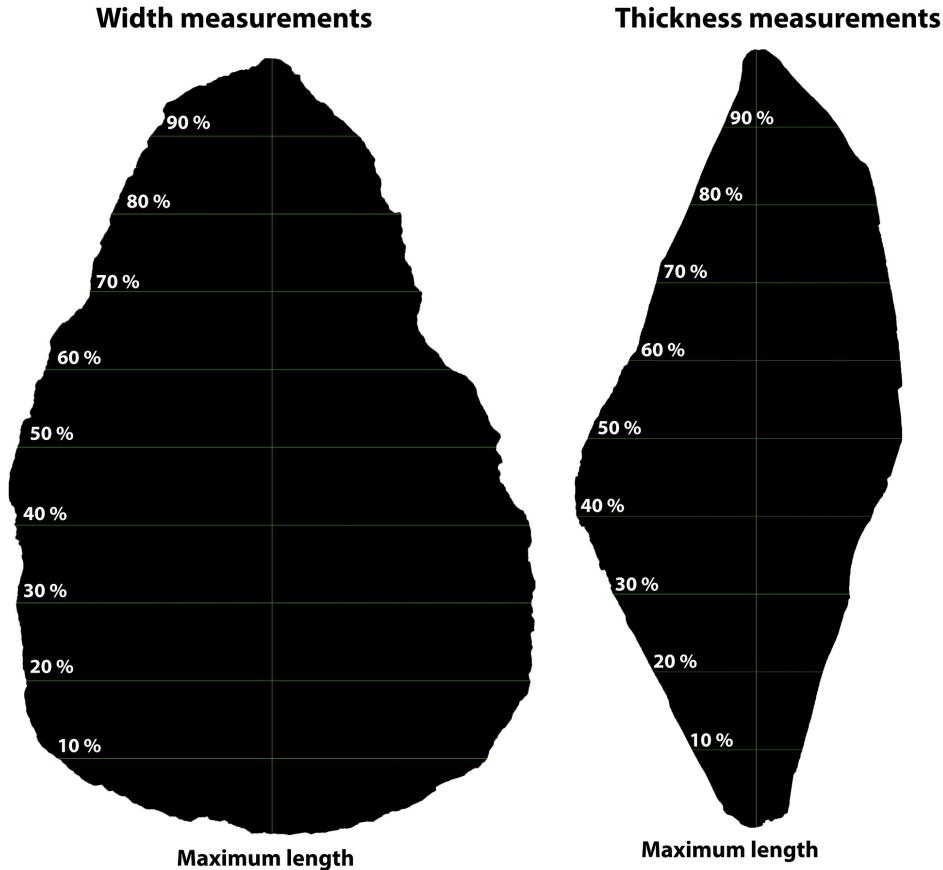


Figure 2: A visual demonstration of the handaxe measurement protocol using Image J (after Pargeter et al. 2019: Figure 5).

236 **2.4 Statistical analyses**

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

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

259 3 Results

260 3.1 Principal component analysis

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

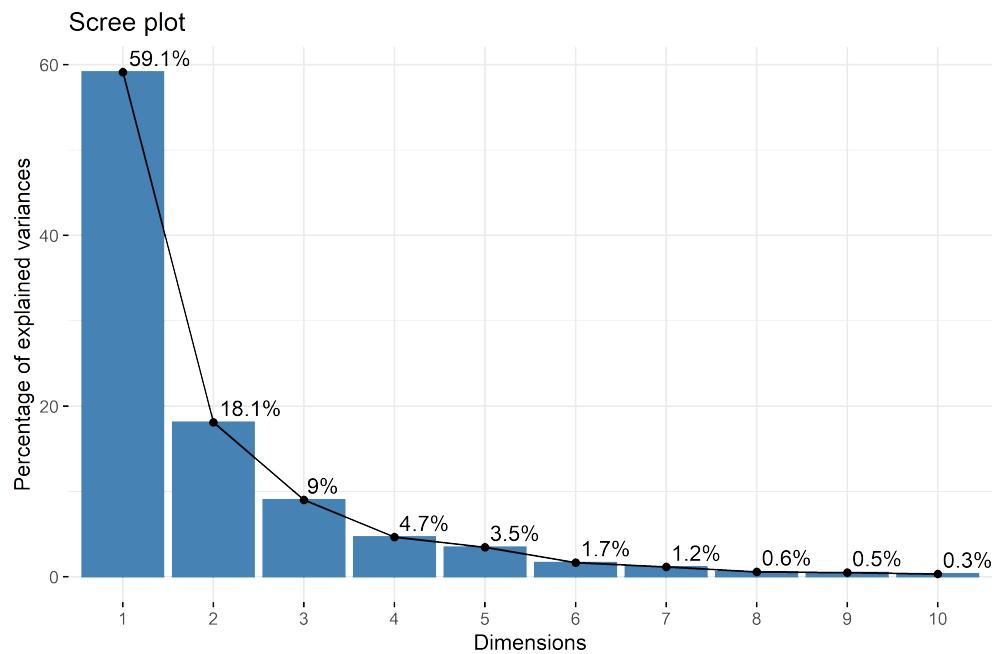


Figure 3: A scree plot showing the percentage of explained variances of the first 10 principal components.

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

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

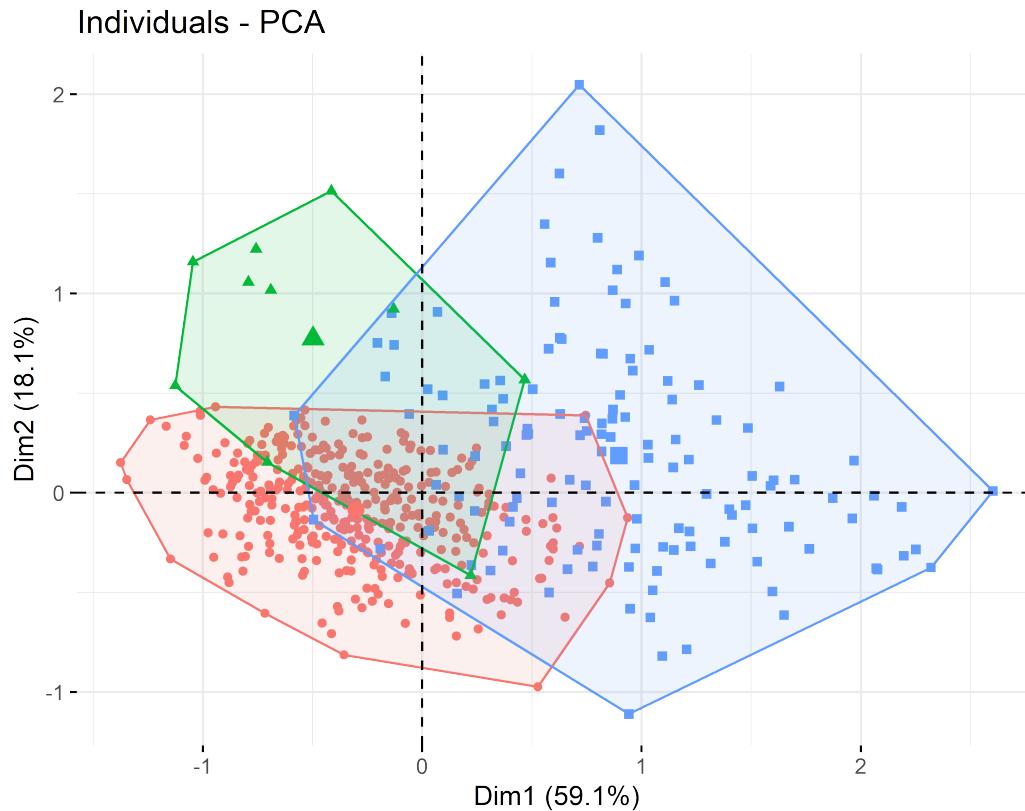


Figure 4: A principal component scatter plot of handaxes from the groups of Boxgrove (red, n=326), expert (green, n=10), and novice (blue, n=132).

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

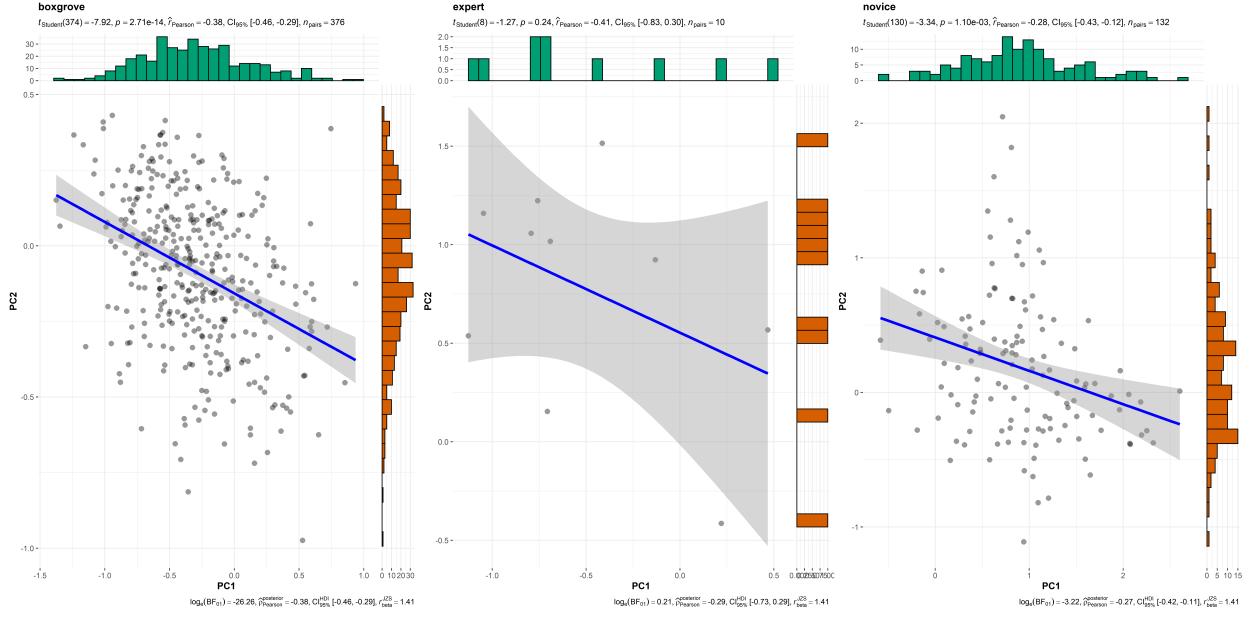


Figure 5: A scatter plot showing the correlation between PC1 and PC2 respectively in the groups of Boxgrove (left, $n=326$), expert (middle, $n=10$), and novice (right, $n=132$). The upper left area in each individual plot displays statistical reporting from a frequentist perspective, including the student-t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

284 3.2 Effects of training

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

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

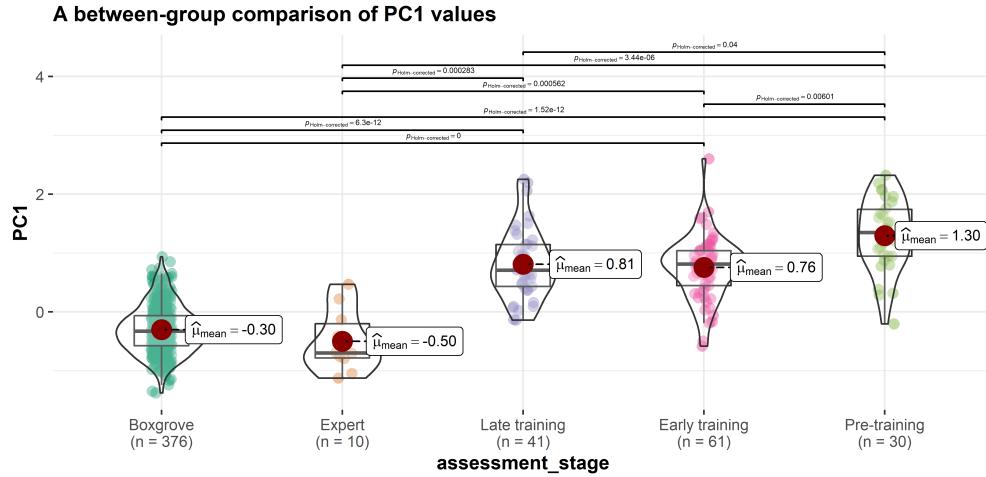


Figure 6: A between-group comparison of PC1 values.

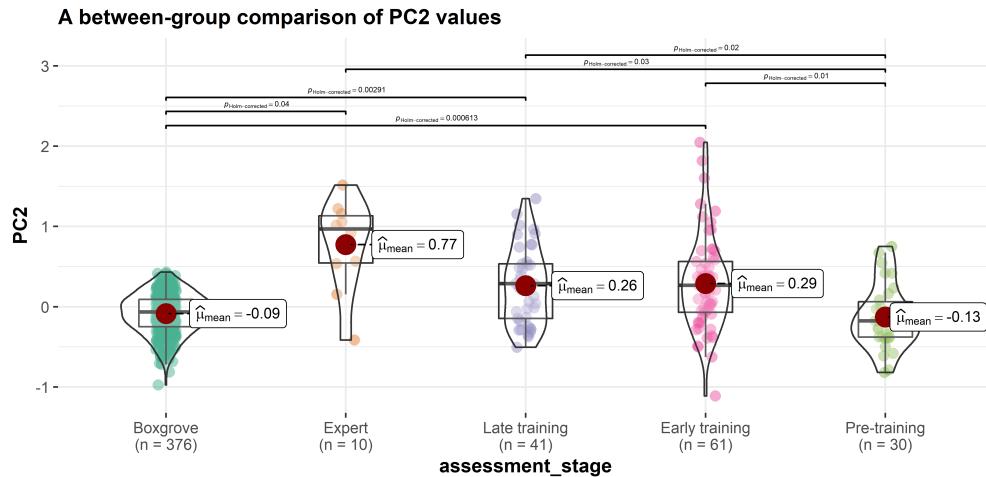


Figure 7: A between-group comparison of PC2 values.

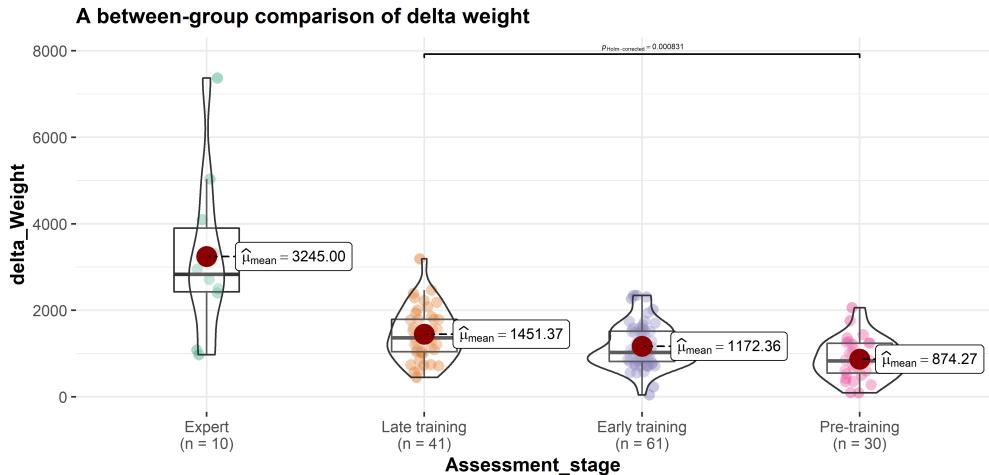


Figure 8: A comparison of the delta weight between the pre-training, early training, late training, and the expert group.

302 4 Discussion

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

321 1998: 384-394; [Roberts & Pope, 2009](#)), although the validity of differentiating purcussor types
322 (hard hammerstone, soft hammerstone, and antler hammer) based on flake attributes has been
323 challenged by other experimental studies([Driscoll & García-Rojas, 2014](#)). It should be noted that
324 both our experts and novices frequently used soft hammers in the production of experimental
325 assemblages. In the skill acquisition experiments, novice knappers were explicitly taught to
326 switch to the soft hammer for thinning purposes, but some of them did not follow the instruction
327 during the assessment. On the other hand, it has also been shown that hard hammers can also
328 be used to achieve similar thinning results ([Bradley & Sampson, 1986](#); [Pelcin, 1997](#)), and the
329 replicas produced by Bruce Bradley in our expert reference collection did not involve the use of
330 soft hammers.

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

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

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

381 Moreover, this follow-up project further adds the samples produced by the Late Acheulean
382 toolmaker as a new benchmark to deepen our understanding of this issue. As previously shown

383 in Key's (2019) previous finding regarding Boxgrove, it is noteworthy how constrained the range
384 of Boxgrove assemblage morphological variation is as measured by both PC1 and PC2 even when
385 compared with the modern expert group (**Figure 4**), especially given the fact that it has the largest
386 sample size among all studied groups. Some potential explanations for this phenomenon include
387 1) the strong idiosyncrasy of individual expert knappers shaped by their own unique learning
388 and practice experience; 2) the present-day skill shortage of our expert knapper as compared
389 with Boxgrove knappers despite their multiple years of knapping practice (Milks, 2019); and/or
390 3) modern knappers' skill level was affected by time constraints when they were requested to
391 produce the reference collections (Lewis et al., 2022; Schillinger et al., 2014b).

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

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

431 research questions given the data available is key to revealing new novel insights into the studied
432 topic. Moreover, we believe that this type of research has a strong contemporary relevance due
433 to the continued influence of the COVID-19 on fieldwork-related travel and direct access to
434 archaeological artifacts (Balandier et al., 2022; Ogundiran, 2021).

435 5 Conclusions

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

460 6 CRediT authorship contribution statement

461 **Cheng Liu:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing
462 – original draft, Writing – review & editing. **Nada Khreisheh:** Investigation, Writing – review &
463 editing. **Dietrich Stout:** Conceptualization, Investigation, Resources, Funding acquisition, Super-
464 vision, Writing – original draft, Writing – review & editing. **Justin Pargeter:** Conceptualization,
465 Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

466 7 Declaration of competing interest

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

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