

¹ Detecting skill level and mental templates in Late Acheulean
² biface morphology: Archaeological and experimental
³ insights

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⁵ **Abstract**

⁶ Despite the extensive literature focusing on Acheulean bifaces, especially the sources and
⁷ meaning of their morphological variability, many aspects of this topic remain elusive. Among
⁸ many factors identified to contribute to the considerable variation of biface morphology, skill
⁹ level and mental templates have been frequently cited. Here we present results from a multi-
¹⁰ disciplinary study of Late Acheulean handaxe-making skill acquisition involving twenty-six
¹¹ naïve participants trained for up to 90 hours in Late Acheulean style handaxe production and
¹² three expert knappers. We compare their handaxe to the Late Acheulean handaxe assemblage
¹³ from Boxgrove, UK. Through the principal component analysis of morphometric data derived
¹⁴ from images, our study suggested that both skill level and mental template have a relatively
¹⁵ clear manifestation in different aspects of biface morphology, where the former is related to
¹⁶ cross-sectional thinning (PC1) while the latter relates to handaxe elongation and pointedness
¹⁷ (PC2). Moreover, we also evaluated the effects of training using the data from a 90-hour long
¹⁸ knapping skill acquisition experiment and found that reaching the skill level of modern experts
¹⁹ requires more training time than was permitted in this extensive and long-running training
²⁰ program. Our study demonstrated the potential of experimental archaeology and digital
²¹ photographs in revealing new insights from old archaeological assemblages.

²² **Keywords:** Late Acheulean; Biface production; Boxgrove; Experimental archaeology; Skill
²³ level; Mental template

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40 **1 Introduction**

41 The morphological variability of Acheulean bifaces has been one of the most well-studied and
 42 well-published topics in paleolithic archaeology (Key & Lycett, 2019; Petraglia & Korisettar, 1998;
 43 White, 1998). Despite the recurrent narrative emphasizing the homogeneity and longevity of
 44 biface assemblage on a global scale and the conservatism behind this phenomenon that evokes
 45 genetic explanations (Corbey et al., 2016; Corbey, 2020; Richerson & Boyd, 2005; Sterelny, 2004),
 46 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 have been identified to contribute to the great variation
 50 of biface morphology, including but not limited to raw materials (Eren et al., 2014; Lycett et
 51 al., 2016; Sharon, 2008), percussor properties (Shipton et al., 2009), function (Key et al., 2016;
 52 Key & Lycett, 2017; Kohn & Mithen, 1999; Machin et al., 2007; White & Foulds, 2018), reduction
 53 method/intensity (Shipton et al., 2009; Shipton & Clarkson, 2015), learning processes (Kempe et
 54 al., 2012; Lycett et al., 2016), skill level (Caruana & Herries, 2021; Herzlinger et al., 2017; Stout et
 55 al., 2014), mental template (García-Medrano et al., 2019; Hutchence & Scott, 2021). From this
 56 extensive list, skill level and mental template have been repeatedly mentioned and discussed in
 57 the now extensive corpus of biface studies.

58 In its classical definition, the term mental template indicates that the “idea of the proper form
 59 of an object exists in the mind of the maker, and when this idea is expressed in tangible form in

60 raw material, an artifact results" (Deetz, 1967: 45). This concept lies at the very foundation of the
61 cultural-historical approach in that the identification of archaeological cultures is based on the
62 existence of distinct mental templates in a given spatial-temporal framework. Early researchers,
63 whether explicitly or implicitly, often endorsed this conceptual framework and actively applies it
64 in the typological analysis of bifaces at the regional level (Roe, 1969; Wenban-Smith et al., 2000;
65 Wenban-Smith, 2004). Combined with the production of large flakes, the emergence of mental
66 templates (or "imposed form") has been recognized as a major technological innovation of the
67 Acheulean compared with the Oldowan (Isaac, 1986). For a decade or so, this concept has been
68 less frequently used, since it was criticized for a) its normative and static assumption (Lyman &
69 O'Brien, 2004), b) ignorance of other competing factors such as raw material constraints (White,
70 1995), and c) the lack of rigorous studies of its corresponding cognitive processes. To avoid the
71 historical baggage associated with this controversial term, some researchers have also developed
72 alternative frameworks such as "design imperatives" purely derived from ergonomic principles,
73 which refers to a set of minimum features shared by all handaxes including glob-but, forward
74 extension, support for the working edge, lateral extension, thickness adjustment, and skewness
75 (Gowlett, 2006; Wynn & Gowlett, 2018).

76 Until very recently, several researchers have actively addressed the above-mentioned critiques
77 and reconceptualized the mental template in the study of biface morphology. Hutchence and
78 Scott (2021), for example, leveraged the theory of "community of practice" (Wenger, 1998) to
79 explain the stability of Boxgrove handaxe design across multiple generations, especially how
80 the social norms behind the consolidated material expressions were developed and negotiated
81 by individuals in a group who have a shared history of learning. They further emphasized that
82 emergent actions of individual knappers also contribute greatly to the shape of Boxgrove han-
83 daxes but they were simultaneously constrained by the imposition of social norms. This view
84 also somewhat echoes the "individualized memic construct" proposed by McNabb et al. (2004),
85 which tries to provide a more balanced perspective incorporating both individual agency and
86 social learning. Furthermore, raw material is often treated as a crucial variable to be controlled at
87 the very beginning of a research design focusing on mental templates. This is best exemplified by
88 an experimental study of García-Medrano et al. (2019), where they carefully chose experimental
89 nodules mirroring those found in archaeological context in composition, size, and shape. In
90 terms of the cognitive mechanisms behind mental templates, Ho and colleagues (2022) recently
91 developed a series of navigation experiments demonstrating the externalization of the planning

92 process to simple geometric representations instead of a complete representation of the given
93 task, featuring both the efficiency and flexibility given the limited cognitive resources., Their
94 experimental design has the potential to be transferred into a research setting aiming at directly
95 testing the planning of knapping behaviors and elucidating how “mental templates” are con-
96 structed and perceived in brains. In short, when exercised with proper caution, the concept of
97 mental template still has its value in our study of biface morphological variation, which can be
98 further dissected into a series of shape variables corresponding to pointedness and elongation,
99 among other things.

100 Following the reconceptualization of the concept of mental template, one possible way of defining
101 skill is the capacity for a knapper to realize mental templates using the resources available (Roux
102 et al., 1995: 66). This version of conceptualization, particularly relevant when it comes to motor
103 skills such as knapping, can be dismantled into two mutually dependent aspects, namely the
104 intentional aspect (goal/strategic planning) and the operational aspect (means/motor execution)
105 (Connolly & Dalgleish, 1989). It also roughly corresponds to the well-known dichotomy developed
106 by French lithic analysts of “*connaissance*” (abstract knowledge) and “*savoir-faire*” (practical
107 know-how) (Pelegrin, 1993). As Stout (2002: 694) noted, the acquisition of skill is deeply rooted
108 in its social context, and it is not composed of “some rigid motor formula” but “how to act in
109 order to solve a problem.” This ecological notion of skill somewhat mirrors Hutchence and
110 Scott’s (2021) reconceptualization of the mental template in that they both refute the idea that
111 technology is simply an internal program expressed by the mind and they prefer a dynamic
112 approach emphasizing the interaction between perception and action. The manifestations of
113 skill in materialized form display a great amount of variation, but ethnoarchaeological studies
114 have repeatedly suggested that skills can be improved through practice as perceived by the local
115 practitioners. It is thus possible to evaluate the skill levels reflected in knapping products (Roux
116 et al., 1995; Stout, 2002). When contextual information is less readily available as in the Late
117 Acheulean archaeological assemblages, how to properly operationalize and measure knapping
118 skills has been a methodological issue receiving much attention among archaeologists (Bamforth
119 & Finlay, 2008; Kolhatkar, 2022). In addition to measurements that can be almost applied in
120 any lithic technological system such as raw materials, platform preparation, as well as hinges,
121 in the context of biface technology, symmetry (Hodgson, 2015; Hutchence & Debackere, 2019)
122 and cross-sectional thinning (Caruana, 2020; Pargeter et al., 2019; Stout et al., 2014) have been
123 frequently quoted as reliable and distinctive indicators of the skill level as supported by several

¹²⁴ experimental studies. These two features have also been commonly used as standards for dividing
¹²⁵ Early Acheulean and Late Acheulean ([Callahan, 1979](#); [Clark, 2001](#); [Schick & Toth, 1993](#)).

¹²⁶ Drawing on these two lines of literature, we aim to explore the possibility of differentiating skill
¹²⁷ level and mental template and the interaction between the two through a comparative study of an
¹²⁸ archaeological biface assemblage known for its remarkable dexterity, a reference biface collection
¹²⁹ produced by modern knapping experts, and an experimental biface sample produced by modern
¹³⁰ novice knappers. Since the novice biface collection is generated from a 90-hour skill acquisition
¹³¹ experiment, we also have the precious opportunity to introduce the diachronic dimension of
¹³² training time and interrogate its impact on the variables of interest. As such, we propose the
¹³³ following two interconnected research questions in this article: 1) Can skill level and mental
¹³⁴ template be efficiently detected from biface morphometric data? 2) How does training affect
¹³⁵ novices' performance in these two aspects?

¹³⁶ 2 Materials and methods

¹³⁷ 2.1 Boxgrove biface collection

¹³⁸ The archaeological site of Boxgrove is located in the former Eartham quarry, Boxgrove, West
¹³⁹ Sussex, featuring a long sequence of Middle Pleistocene deposit ([Pope et al., 2020](#); [Roberts &](#)
¹⁴⁰ [Parfitt, 1998](#)). This 500-ka-old site has documented exceedingly rich details of Lower Paleolithic
¹⁴¹ hominins' subsistence behaviors ([Smith, 2013, 2012](#)) and their paleoenvironmental contexts
¹⁴² ([Holmes et al., 2010](#)). In addition to the presence of one of the earliest hominin fossil (*Homo*
¹⁴³ *heidelbergensis*, [Hillson et al., 2010](#)) and bone assemblages with anthropogenic modifications
¹⁴⁴ in northern Europe ([Bello et al., 2009](#)), Boxgrove is mostly known for its large sample size of
¹⁴⁵ Late Acheulean-style flint handaxes and the high dexterity reflected in their manufacture. As
¹⁴⁶ such, it has received wide research attention in the past two decades regarding the relationships
¹⁴⁷ between technology, cognition, and skills ([García-Medrano et al., 2019](#); [Iovita et al., 2017](#); [Iovita](#)
¹⁴⁸ & [McPherron, 2011](#); [Shipton & Clarkson, 2015](#); [Stout et al., 2014](#)). To identify the morphological
¹⁴⁹ manifestation of knappers' dexterity in our study, we selected a complete handaxe assemblage
¹⁵⁰ (n=326) previously analyzed and reported in digital formats by Iovita and McPherron ([Iovita &](#)
¹⁵¹ [McPherron, 2011](#)), which is currently curated at the Franks House of the British Museum ([Iovita et](#)
¹⁵² [al., 2017](#)). The digital photographs are taken of each handaxe at a 90° angle, which was oriented

153 with the tip to the right of the photos, and the camera faces the most convex surface of the
154 handaxe ([Iovita & McPherron, 2011](#)).

155 **2.2 Experimental biface collection**

156 The biface experimental replicas used in this study comprised two sub-collection. The first
157 sub-collection includes 10 bifaces knapped by three expert knappers, including Bruce Bradley
158 (n=4), John Lord (n=3), and Dietrich Stout (n=3) ([Stout et al., 2014](#)). These handaxes were made
159 for previous research projects, which similarly aimed to approximate ‘Late Acheulean’ handaxes
160 explicitly comparable to the Boxgrove assemblage ([Faisal et al., 2010](#); [Stout et al., 2014](#); [Stout et al.,](#)
161 [2011](#)). The second sub-collection is produced from a 90-hour handaxe knapping skill acquisition
162 experiment ([Bayani et al., 2021](#); [Pargeter et al., 2020](#); [Pargeter et al., 2019](#)), where 30 adults with
163 no previous experience in knapping were recruited from Emory University and its surrounding
164 communities and requested to make 132 bifaces in total. Among these 30 adult participants, 17
165 have gone through multiple one-to-one or group training sessions that amounted to 89 hours
166 in maximum, while the remaining 13 were assigned to the controlled group, where no formal
167 training is given. As part of the preparation efforts, the experimental team spalled the Norfolk
168 flints acquired through [Neolithics.com](#) into flat blanks of similar size and shape for training and
169 assessments. The mechanical properties of these raw materials are comparable to the ones used
170 in Boxgrove in that they are both fine-grained and highly predictable in fracturing process.

171 In this experiment, all research participants participated in the initial assessment (assessment 1 in
172 our data set) before formal training, where they each produced a handaxe after watching three 15-
173 minute videos of Late Acheulean style handaxes demonstrated by expert knappers and examining
174 four Late Acheulean style handaxe replicas. Training was provided by verbal instruction and
175 support from the second author, an experienced knapping instructor ([Khreisheh et al., 2013](#))
176 with 10 years knapping practice and specific knowledge of Late Acheulean technology including
177 the Boxgrove handaxe assemblage. She was present at all training sessions to provide help and
178 instruction to participants. All training occurred under controlled conditions at the outdoor
179 knapping area of Emory’s Paleolithic Technology Lab, with knapping tools and raw materials
180 provided. All participants were instructed in basic knapping techniques including how to select
181 appropriate percussors, initiate flaking on a nodule, maintain the correct flaking gestures and
182 angles, prepare flake platforms, visualize outcomes, deal with raw material imperfections, and

183 correct mistakes. Handaxe-specific instruction included establishment and maintenance of
184 a bifacial plane, cross-sectional thinning, and overall shaping. The training emphasized both
185 aspects of handaxe making technical skill (the importance of producing thin pieces with centered
186 edges) as well as mental template related markers (symmetrical edges).

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

197 2.3 Lithic analysis

198 To better understand the morphological variation of Boxgrove biface collection, we adopted a
199 standardized analytical procedure to extract the morphometric information from 752 photos of
200 the studied samples ([Iovita & McPherron, 2011](#)), which include both the front and lateral views
201 of a given specimen. First, we used Adobe Photoshop to conduct a batch transformation of
202 the samples' pixel scale into a real-world measurement scale based on the fixed photographic
203 setting. This is then followed by the batch conversion of color photographs to a black-and-
204 white binary format. Subsequently, we cropped the silhouettes of bifaces one by one using
205 the Quick Selection Tool in Adobe Photoshop. The metric measurements were conducted in
206 ImageJ ([Rueden et al., 2017](#)), where we employed a custom ImageJ script ([Pargeter et al., 2019](#))
207 to measure the maximum length, width, and thickness of a given silhouette. The width and
208 thickness measurements are taken at 10% increments of length starting at the tip of each biface
209 (**Figure 1**), which eventually leads to 19 morphometric variables in total (1 length measurement,
210 9 width measurements, and 9 thickness measurements). Finally, we calculated the geometric
211 means of all 19 linear measurements to create a scale-free data set that preserves the individual
212 morphological variation at the same time ([Lycett et al., 2006](#)), which also at least alleviate the

213 effect of resharpening process to some extent. The same procedure was also applied to the
214 morphometric analyses of the experimental biface collection, which was partially published in
215 Pargeter et al. (2019).

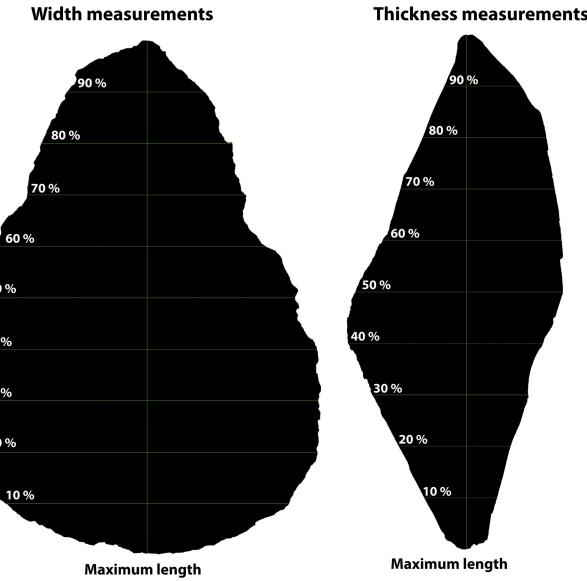


Figure 1: A visual demonstration of the biface measurement protocol using Image J (after Pargeter et al. 2019: Figure 5).

216 2.4 Statistical analyses

217 Given the number of variables involved in this study, we used principal component analysis (PCA)
218 to reduce the dimension and identify the possible patterns in this morphometric data set, which
219 is one of the most used techniques in similar studies (García-Medrano, Maldonado-Garrido,
220 et al., 2020; García-Medrano, Ashton, et al., 2020; Herzlinger et al., 2017; Iovita & McPherron,
221 2011; Shipton & Clarkson, 2015; Stout et al., 2014). To detect the effect of training on novices'
222 performance as compared with archaeological samples and biface made by experts, we also
223 compare the corresponding metrics built on PCA across different training periods and across
224 all groups using the Games-Howell nonparametric post-hoc test, which does not rely on the
225 assumptions of equal sample sizes and equal variance. This study adheres to the principles of
226 reproducibility and data transparency of archaeological research by depositing all the codes and
227 data sets involved in an open-access online repository (Marwick, 2017), which can be accessed
228 through the author's Github (<https://github.com/Raylc/PaST-pilot>).

²²⁹ **3 Results**

²³⁰ **3.1 Principal component analysis**

²³¹ Our analysis suggested that the first two components already explain 77.2% of the variation for
²³² the entire morphometric data set composed of 19 variables (**Figure 2**), which is a rather decent
²³³ explained variance ratio to avoid overfitting. We then decided to focus on and further interpreted
²³⁴ the implications of these first two components based on their relationships between variables
²³⁵ (**Table 1**). The first principal component (PC1) indicates the overall cross-sectional thickness as it
²³⁶ is positively correlated with all thickness measurements while negatively correlated with all other
²³⁷ measurements. That being said, a higher PC1 value indicates a thicker biface, and vice versa. The
²³⁸ second principal component (PC2) tracks the elongation and pointedness based on its positive
²³⁹ relationship with maximum length and bottom width/thickness. As PC2 increases, a biface will
²⁴⁰ be generally longer and more pointed since its bottom part will be bulkier.

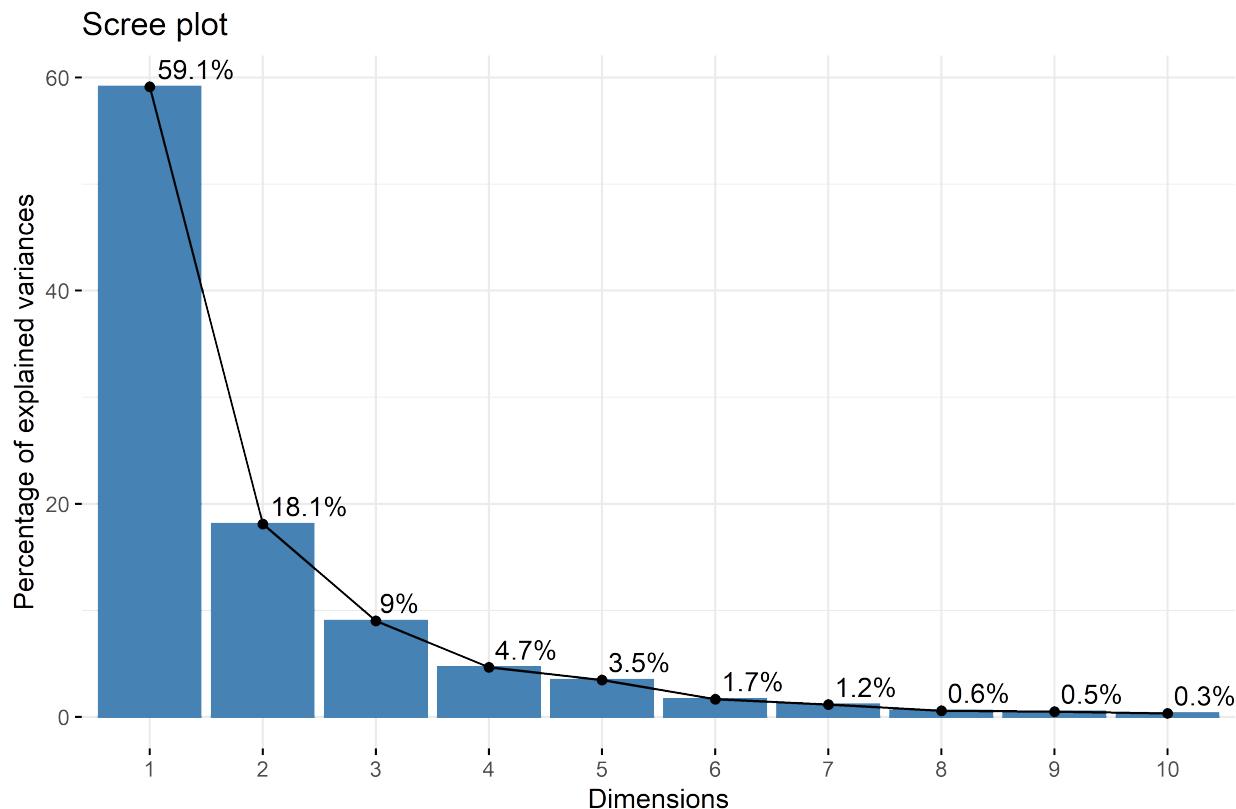


Figure 2: A scree plot showing the percentage of explained variances of the first 10 principal components.

Table 1: Variable loadings for the first two principal components

X	Dim.1	Dim.2
width_0.1	-0.1131312	-0.1256408
width_0.2	-0.1419554	-0.1326946
width_0.3	-0.1684170	-0.1232328
width_0.4	-0.1867226	-0.0966578
width_0.5	-0.2037483	-0.0651505
width_0.6	-0.2121330	-0.0197136
width_0.7	-0.2083163	0.0232790
width_0.8	-0.1885821	0.0661257
width_0.9	-0.1447319	0.0805702
thickness_0.1	0.0142639	-0.0240388
thickness_0.2	0.0247137	-0.0227114
thickness_0.3	0.0435524	-0.0093580
thickness_0.4	0.0667936	0.0047643
thickness_0.5	0.0893523	0.0261202
thickness_0.6	0.1083112	0.0484852
thickness_0.7	0.1288346	0.0628567
thickness_0.8	0.1444047	0.0659257
thickness_0.9	0.1308949	0.0487419
max_length	-0.3626265	0.2507234

241 A closer look at the principal component scatter plot ([Figure 3](#)) yields the clustering of different
 242 groups of bifaces. The majority of Boxgrove bifaces occupy an area featuring negative values of
 243 both PC1 and PC2. The expert group is similar to the Boxgrove group in PC1, while the former has
 244 a relatively higher PC2 value than the latter on average. The group of novice displays the highest
 245 level of variability, however, it is rather pronounced that most bifaces made by novices have a
 246 positive PC1 value that is different from both the groups of Boxgrove and experts.

Individuals - PCA

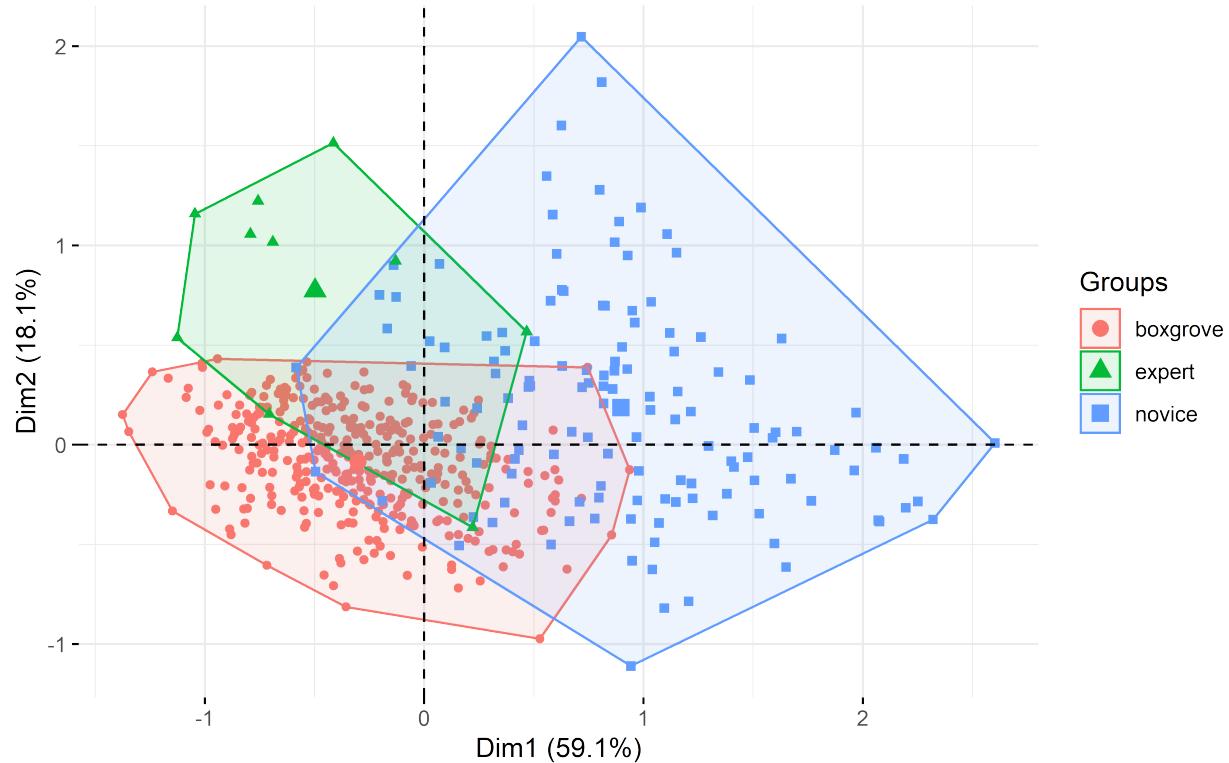


Figure 3: A principal component scatter plot of bifaces from the groups of Boxgrove (red, n=326), expert (green, n=10), and novice (blue, n=132).

²⁴⁷ In addition, visual inspection of the principle component scatter plot (Fig.) suggested that
²⁴⁸ PC1 and PC2 might be negatively correlated within the Boxgrove and Expert groups. To test
²⁴⁹ this, we conducted a series of exploratory plotting and statistical analyses of the PC values of
²⁵⁰ three groups analyzed in our analysis (**Figure 4**). Across all three groups, a negative correlation has
²⁵¹ been displayed between the PC1 and PC2 values, although this trend is not statistically significant
²⁵² ($r=-0.41$, $p= 0.24$) in the expert group, probably because of its small sample size.

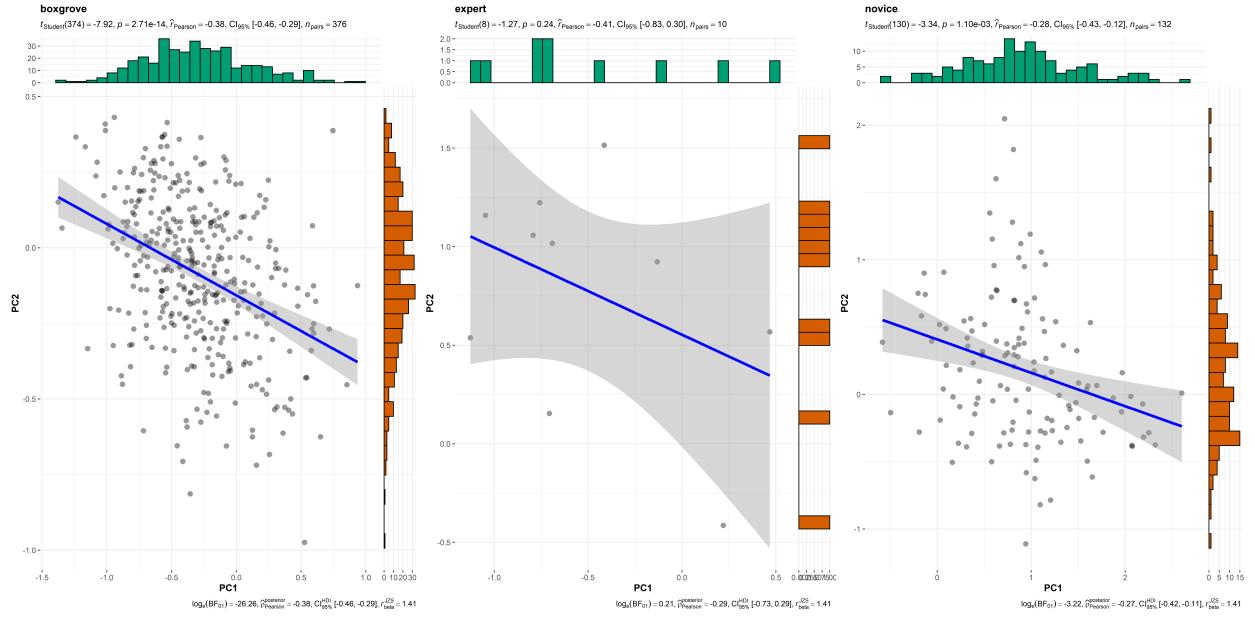


Figure 4: A scatter plot showing the correlation between PC1 and PC2 respectively in the groups of Boxgrove (left, $n=326$), expert (middle, $n=10$), and novice (right, $n=132$).

253 3.2 Effects of training

254 We extracted the PC1 and PC2 values of individual bifaces and compared them between different
 255 groups. More specifically, the novice group was divided into three sub-groups based on their
 256 training stages as specified in the method section. As such, we found that for PC1 values (**Figure**
 257 **5**), the only two group comparisons that are **not** statistically significant are the one between
 258 Boxgrove and Expert ($t = -1.65, p > 0.05$) and the one between Early training and Late training
 259 stages ($t = -0.649, p > 0.05$), which at least partially confirms our visual observation of the
 260 general PCA scatter plot. Likewise, for PC2 values (**Figure 6**), the group comparison between the
 261 Early training and Late stages again is **not** statistically significant ($t = 0.333, p > 0.05$). However, a
 262 rather surprising result here is that the mean PC2 value difference between the Pre-training group
 263 and Boxgrove is also **not** statistically significant ($t = -0.818, p > 0.05$).

A between-group comparison of PC1 values

$$F_{\text{Welch}}(4, 44.97) = 119.31, p = 2.45\text{e-}23, \widehat{\omega_p^2} = 0.90, \text{CI}_{95\%} [0.86, 1.00], n_{\text{obs}} = 518$$

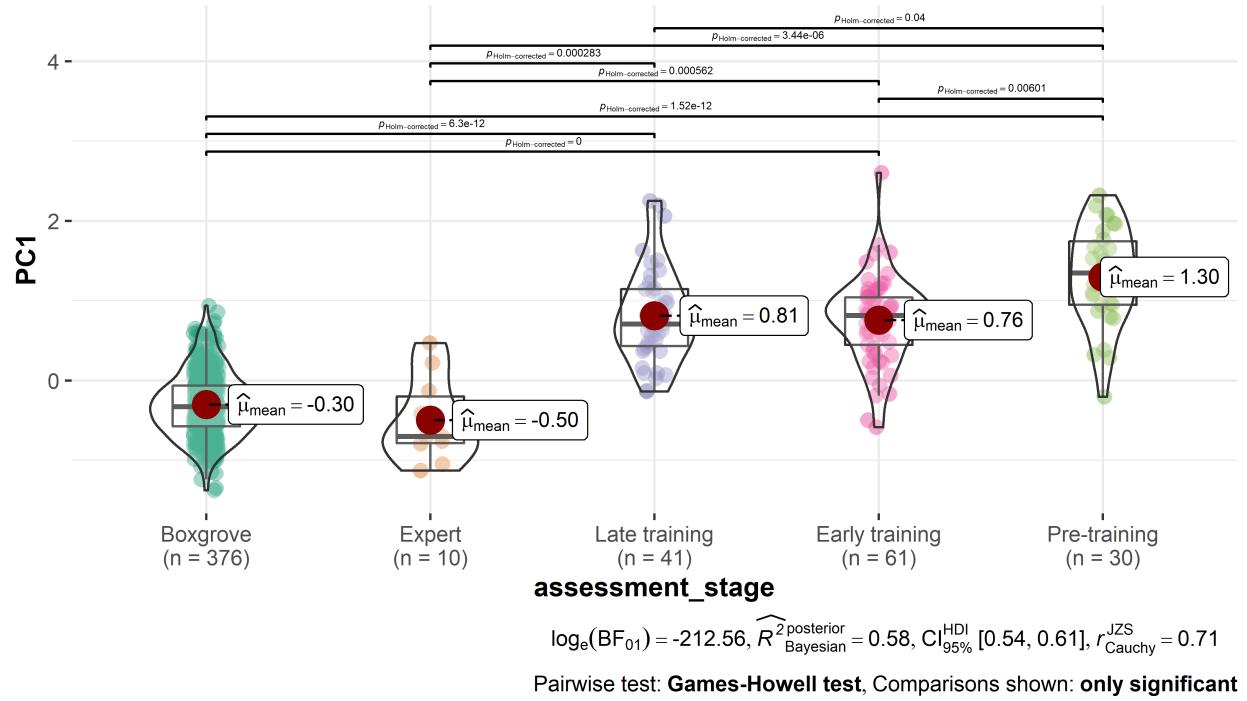


Figure 5: A between-group comparison of PC1 values.

A between-group comparison of PC2 values

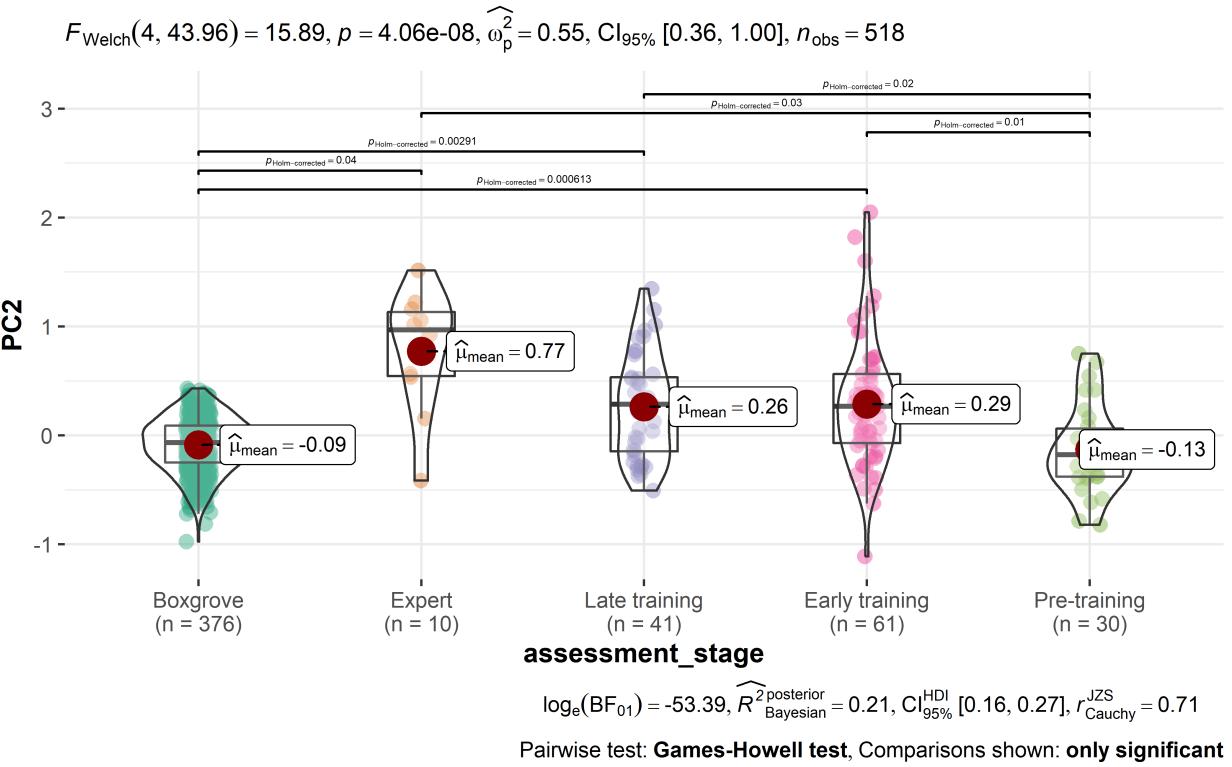


Figure 6: A between-group comparison of PC2 values.

264 4 Discussion

265 In accordance with the existing literature on biface knapping skill (Callahan, 1979; Caruana, 2020;
 266 Stout et al., 2014), the results of PCA suggested that PC1 (cross-sectional thinning) is a robust
 267 indicator of skill level as it is a common feature shared by modern expert knapper and Boxgrove
 268 knappers. Thinning is regarded as a technique requiring a high knapping skill level because
 269 it requires one to carefully detach flakes in an invasive manner while not breaking the biface
 270 into several pieces, serving the purpose of achieving the desired convexity and/or volume. This
 271 procedure involves precise control of striking forces, strategic choice of platform external angle,
 272 and attentive preparation of bifacial intersection plane, all of which were part of our experimental
 273 training program (Callahan, 1979; Caruana, 2022; Pargeter et al., 2020; Shipton et al., 2013; Stout
 274 et al., 2014). Experimental studies have also shown that the thinning stage of biface produce often
 275 involves the use of soft hammers, which is also supported by indirect archaeological evidence
 276 of flake attributes from Boxgrove (Roberts & Parfitt, 1998: 384-394; Roberts & Pope, 2009). This

277 also reflects the majority of samples in both our expert and novice experimental assemblages. In
278 the skill acquisition experiments, novice knappers have been explicitly taught to switch to the
279 soft hammer for thinning purposes, but some of them did not follow the instruction during the
280 assessment. On the other hand, it has also been shown that hard hammers can also be used to
281 achieve similar thinning results (Bradley & Sampson, 1986; Pelcin, 1997), corresponding to the
282 cases of replicas produced by Bruce Bradley and a few novices in our study.

283 Given the dissimilarity of PC2 (elongation and pointedness) values between archaeological and
284 experimental samples and its similarity among modern knappers, we argue that this dimension
285 reflects different mental templates, where the Boxgrove assemblage displays an ovate shape
286 featuring a wider tip while the experimental assemblages are characterized by a more pointed
287 shape with a longer central axis. This divergence of group-level aesthetic choices can be best
288 explained under the theoretical framework of the communities of practice (Wenger, 1998) as
289 advocated by Hutchence and Scott in biface analysis(2021). The most common form of learning
290 in the experiment occurred in the group condition, where the instructor taught multiple novices
291 at the same time and novices have the chance to also communicated and learned from their
292 peers. Unfortunately, the biface data from the instructor (N. Khreisheh) are unavailable, but it
293 should be noted that the instructor has learned how to knap and how to teach knapping from one
294 of our expert knapper (Bruce Bradley). This cascading effect of social learning might explain why
295 there is a shared mental template between the expert group and the novice group after training.

296 In terms of our second research question, this study shows that training does have an immediate
297 intervention effect (pre-training vs. post-training) in both PC1 (skill level) and PC2 (mental tem-
298 plate). Nonetheless, once the training has been initiated, its effects across different assessments
299 on both dimensions are rather unconsipicous. This finding corroborates what has been suggested
300 in Pargeter et al. (2019) that 90 hours of training for handaxe making is still not enough for
301 novices to reach the skill level as reflected in expert knappers, considering the massive social
302 support involved in the experiment set up including the direct and deliberate pedagogy and
303 the simplified raw material procurement and preparation procedures. This follow-up project
304 further adds the samples produced by the Late Acheulean toolmaker as a new benchmark to
305 deepen our understanding of this issue. It is noteworthy how constrained is the Boxgrove as-
306 semblage morphological variation as measured by both PC1 and PC2 even when compared with
307 the modern expert group (Figure 3), especially given the fact that it has the largest sample size

308 among all studied group. Some potential explanations for this phenomenon include 1) the strong
309 idiosyncrasy of individual expert knappers shaped by their own unique learning and practice
310 experience; and/or 2) the present day-skill shortage of our expert knapper as compared with
311 Boxgrove knappers despite their multiple years of knapping practice (Milks, 2019).

312 The pre-training group is similar to the Boxgrove group in PC2 because these novices lack the
313 ability to effectively reduce the nodules, which are typically flat pre-prepared cortical flakes, to
314 the desired form (Figure 7). If the given nodules already possess an oval morphology like those
315 presented in the Boxgrove assemblage, it is likely the form of end products knapped by novices in
316 the pre-training group will remain roughly unchanged. This explanation is also supported by the
317 comparison of average delta weight, defined as the difference between the weight of handaxe
318 and the weight of nodule, among four groups, where the pre-training group displays the lowest
319 value (Figure 8). On the other hand, the refitting analyses of the Boxgrove handaxe assemblage
320 have suggested that the nodules exploited by knappers inhabiting this site are somewhat bulky
321 and amorphous (Roberts & Parfitt, 1998: 339, 360). These characteristics have been clearly
322 displayed in a recent attempt of slow-motion refitting of a handaxe specimen from Boxgrove
323 GTP17 (<https://www.youtube.com/watch?v=iS58MUJ1ZEo>). As such, behind the resemblance of
324 the pre-training group and the Boxgrove assemblage in PC2 are two types of mechanisms that
325 are fundamentally different from each other, where the latter group exhibits a complex suite of
326 cognitive and motor execution processes to transform the shapeless raw materials to a delicate
327 end product in a given shape.

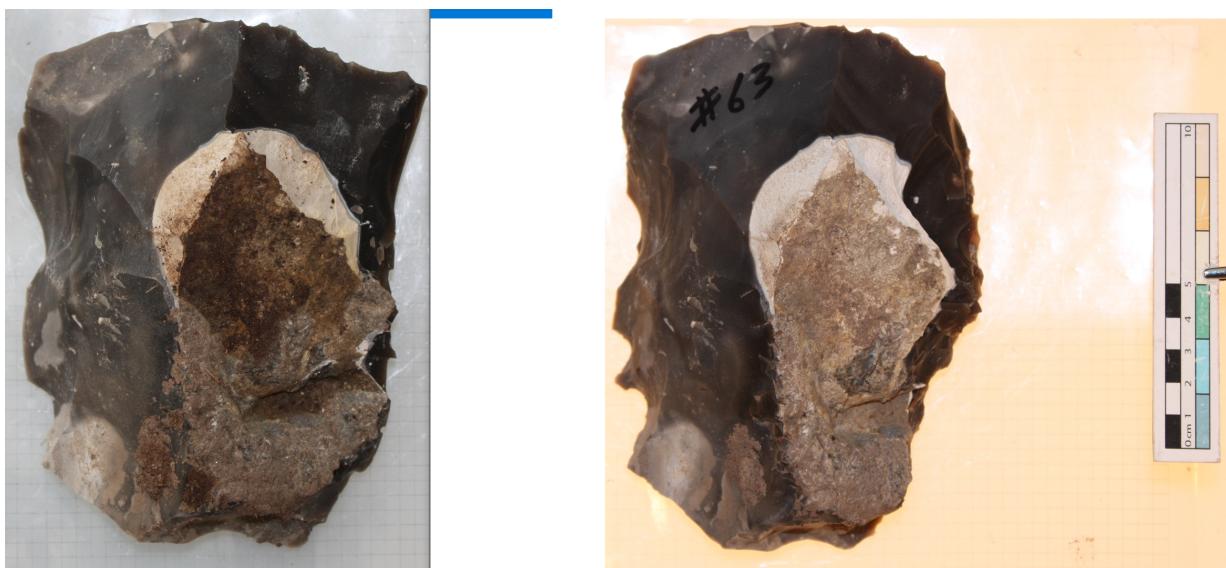


Figure 7: Core 63 before (left) and after knapping(right), showing the minimal morphological change during the process

A between-group comparison of delta weight

$$F_{\text{Welch}}(3, 34.01) = 10.52, p = 4.81e-05, \widehat{\omega_p^2} = 0.43, \text{CI}_{95\%} [0.19, 1.00], n_{\text{obs}} = 142$$

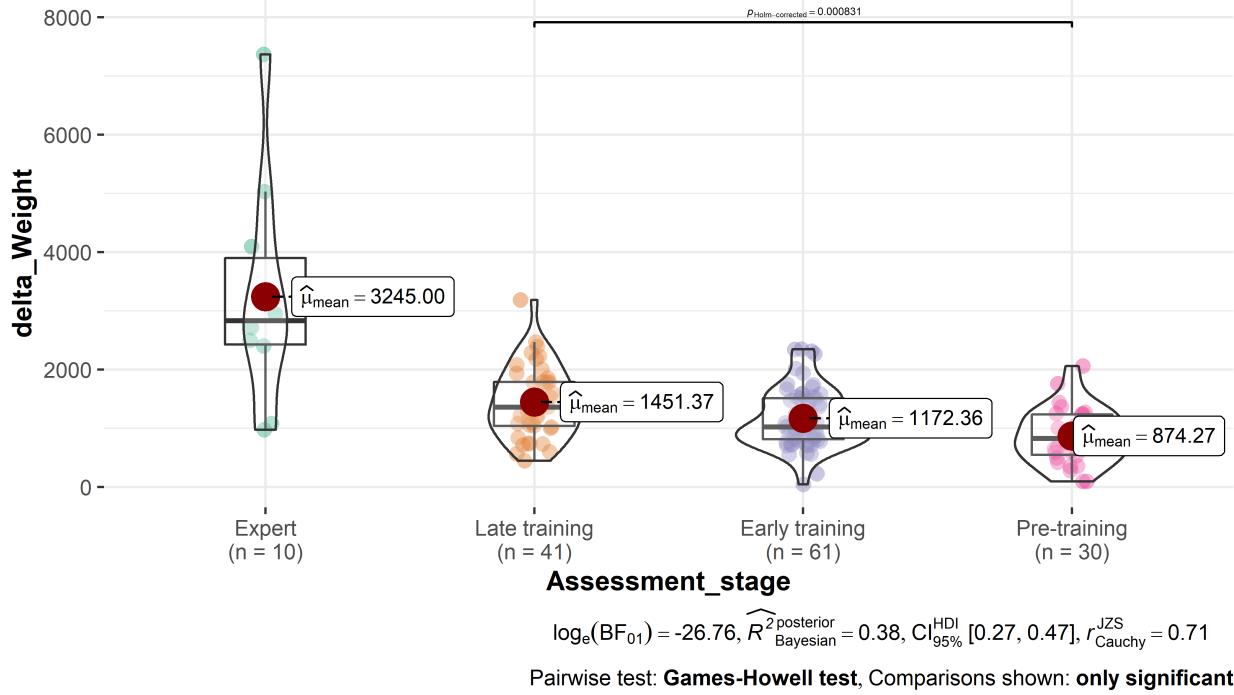


Figure 8: A comparison of the delta weight between the pre-training, early training, late training, and the expert group.

328 Another contribution that we would like to highlight here is that this research project demon-
 329 strates the potential of reusing old archaeological data in digital format to address novel research
 330 questions. In this paper, the main source of archaeological data is a collection of photos produced
 331 more than 10 years ago, and the morphological variation data of the experimental collection are
 332 also derived from photographs instead of remeasurements of the original replicas. Given the
 333 irreversible nature of archaeological excavations, digitized data, be it text, pictures, or videos,
 334 often become the sole evidence that is available for certain research questions. Yet, it has been
 335 widely acknowledged that the reuse of archaeological data has not received enough attention
 336 among researchers in our discipline (Faniel et al., 2018; Huggett, 2018; Moody et al., 2021). Among
 337 many reasons preventing archaeologists from reusing published and digitized data (Sobotkova,
 338 2018), the lack of a standardized practice of and motivation for data sharing is a prominent one
 339 (Marwick & Birch, 2018). As stated in the method section, we addressed this issue by sharing the
 340 raw data and the code for generating the derived data on an open-access repository. Another
 341 major and legitimate concern of archaeological data reuse is their quality. In terms of this aspect,

342 we do acknowledge the limitations of relying on photos when it comes to the more detailed
343 technological analysis of stone artifacts, however, our paper shows that finding the appropriate
344 research questions given the data available is key to revealing new novel insights into the studied
345 topic. Moreover, we believe that this type of research has a strong contemporary relevance due
346 to the continued influence of the COVID-19 on fieldwork-related travel and direct access to
347 archaeological artifacts ([Balandier et al., 2022](#); [Ogundiran, 2021](#)).

348 5 Conclusions

349 Regarding the two research questions we proposed in the beginning, our case study suggested
350 that 1) we can delineate the effects of skill level and mental template through the multivariate
351 analysis of morphometric data, where the former is associated with cross-sectional thinning
352 while the latter is reflected in elongation and pointedness; 2) Training has an immediate effect
353 of sharing a common mental template, but 90 hours of training is still not enough for novice to
354 reach the level of expertise as reflected in modern experienced knappers, let alone the Boxgrove
355 foragers. However, it should be noted that it is not our intention to construct a false binary
356 framework and put these two factors as disconnected and opposite concepts. In the future, more
357 robust experimental studies are needed to deepen our understanding of the relationship between
358 skill acquisition and the morphological variability of bifaces as well as their implications for the
359 biological and cultural evolution of the hominin lineages.

360 6 CRediT authorship contribution statement

361 **Cheng Liu:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing
362 – original draft, Writing – review & editing. **Nada Khreisheh:** Investigation, Writing – review &
363 editing. **Dietrich Stout:** Conceptualization, Investigation, Resources, Funding acquisition, Super-
364 vision, Writing – original draft, Writing – review & editing. **Justin Pargeter:** Conceptualization,
365 Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

³⁶⁶ **7 Declaration of competing interest**

³⁶⁷ The authors declare that they have no known competing financial interests or personal relation-
³⁶⁸ ships that could have appeared to influence the work reported in this paper.

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³⁷⁵ Boxgrove handaxe assemblage.

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