

¹ Imposed form in the Early Acheulean? Evidence from Gona,
² Afar, Ethiopia

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26 **1 Introduction**

27 The imposition of intended form on artifacts has long been viewed as a watershed in human
 28 cognitive and cultural evolution and is most commonly associated with the emergence of “Large
 29 Cutting Tools” (LCTs; cf. Long Core Tools [Shea, (2013)]) in the Early Acheulean (Holloway, 1969;
 30 Isaac, 1976; Kuhn, 2021). However, this interpretation of Acheulean LCTs as intentionally de-
 31 signed artifacts remains controversial. Alternative proposals range from the possibility that LCTs
 32 were unintended by-products of flake production (Noble and Davidson, 1996; Moore and Per-
 33 ston, 2016) to the suggestion that their form was “at least partly under genetic control” (Corbey
 34 et al., 2016: 6). Even accepting that LCT form was to some extent intended, there is substantial
 35 disagreement over the specificity of design. Some analyses have indicated that shape variation
 36 in Acheulean handaxes is largely a result of function-driven resharpening (McPherron, 2000;
 37 Iovita and McPherron, 2011) whereas others find it more likely to reflect normative expectations
 38 of what handaxes should look like (Shipton and Clarkson, 2015a; García-Medrano et al., 2019;
 39 Shipton and White, 2020). Such debates about the shape of Acheulean LCTs may appear nar-
 40 rowly technical but have broad relevance for evolutionary questions, including the origins of
 41 human culture (Shipton and Clarkson, 2015a; Corbey et al., 2016; Tennie et al., 2017; Liu and
 42 Stout, 2023), language (Stout and Chaminade, 2012), teaching (Gärdenfors and Höglberg, 2017),
 43 brain structure (Hecht et al., 2015), and cognition (Stout et al., 2015; Wynn and Coolidge, 2016).
 44 To examine these questions, we studied the complete collection of Early Acheulean (ca. 1.7 –
 45 1.2 Ma) flaked pieces from four sites (BSN17, DAN5, OGS12, and OGS5) in the Gona Project
 46 Area and compared them with all of the flaked pieces from two published Oldowan (>2.5 Ma)
 47 sites at Gona (OGS7 and EG10; Semaw, 2000; Semaw et al., 2003; Stout et al., 2010). By com-
 48 paring variation in overall artifact shape (or “Bauplan” [Lycett and Gowlett, 2008]) to measures
 49 of flaking intensity and coverage, we sought to identify technological patterns that might reveal

50 intent. The possibilities we considered include: a) intentional shape standardization reflecting
51 normative expectations of what handaxes should look like, b) regularities of overall form arising
52 as by-products of the intentional pursuit of particular morpho-functional attributes, and c) the
53 absence of any intentional form imposition as in the case of simple debitage.

54 **1.1 Identifying design**

55 There is a broad consensus that refined handaxes and cleavers from the later Acheulean resulted
56 from procedurally elaborate, skill intensive, and socially learned production strategies ([Sharon, 2009; Stout et al., 2014; García-Medrano et al., 2019; Shipton, 2019; Caruana, 2020; Moore, 2020](#))
57 although debate over the presence of explicit, culturally transmitted shape preferences contin-
58 ues ([Iovita and McPherron, 2011; Wynn and Gowlett, 2018; Moore, 2020; Shipton and White, 2020](#)). There is much less agreement regarding the less heavily worked and formally standar-
59 dized LCTs typical of the earliest Acheulean ([Lepre et al., 2011; Beyene et al., 2013; Diez-Martín et al., 2015; Semaw et al., 2018; Torre and Mora, 2018](#)). Such forms continue to occur with variable
60 frequency in later time periods ([McNabb and Cole, 2015](#)), and may be especially prevalent in
61 eastern Asia ([Li et al., 2021](#)). Although formal types have been recognized in the Early Acheulean
62 and are commonly used to describe assemblages, many workers now see a continuum of mor-
63 phological variation ([Presnyakova et al., 2018; Duke et al., 2021; Kuhn, 2021](#)) including the possi-
64 bility that simple flake production remained an important ([Shea, 2010](#)) or even primary ([Moore and Perston, 2016](#)) purpose of Early Acheulean large core reduction.

65 Typologically, LCTs are differentiated from Mode 1 pebble cores on the basis of size (>10cm)
66 and shape (elongation and flattening) (e.g., [Isaac, 1977](#)). This consistent production of large,
67 flat, and elongated cores in the Achuelean has long been thought to reflect the pursuit of desired
68 functional and ergonomic properties for hand-held cutting tools ([Wynn and Gowlett, 2018](#)). Un-
69 planned flaking can sometimes produce cores that fall into the LCT shape range ([Moore and Perston, 2016](#)) and this is one possible explanation of the relatively small “protobifaces” that
70 occur in low frequencies in Oldowan assemblages ([Isaac and Isaac, 1997](#)). However, the Early
71 Acheulean is clearly distinguished from the Oldowan by the production of larger artifacts ne-
72 cessitating the procurement and exploitation of larger raw material clasts. Although studies of
73 handaxe variation often focus on shape rather than size, this shift is an important aspect of arti-
74 fact design with relevance to both production and function.

80 Production of larger tools was accomplished either through a novel process of detaching and
81 working Large Flake Blanks (LFBs) from boulder cores or simply by using larger cobble and slab
82 cores (Isaac, 1969; Semaw et al., 2018; Torre and Mora, 2018). Both may involve similar flaking
83 “strategies” (e.g., bifacial or multifacial exploitation) to those present in the Oldowan (Duke et
84 al., 2021) but require more forceful percussion to detach larger flakes. This increases the percep-
85 tual motor difficulty of the task (Stout, 2002) and in many cases may have been accomplished
86 using different percussive techniques and supports (Semaw et al., 2009). These new challenges
87 would have increased raw material procurement (Shea, 2010) and learning costs (Pargeter et
88 al., 2019) as well as the risk of serious injury (Gala et al., 2023) associated with tool production.
89 This strongly implies intentional pursuit of offsetting functional benefits related to size increase.
90 These likely included tool ergonomics and performance (Key and Lycett, 2017) as well as flake
91 generation, resharpening, and reuse potential (Shea, 2010). Early Acheulean LCT production is
92 thus widely seen as a part of shifting hominin behavioral ecological strategies including novel
93 resources and mobility patterns (Rogers et al., 1994; Linares Matás and Yravedra, 2021).

94 The degree of intentional design reflected in the shape of Early Acheulean LCTs is more diffi-
95 cult to determine. For example, LFB production using a simple “least effort” bifacial/discoidal
96 strategy will tend to generate predominantly elongated (side or end struck) flakes (Toth, 1982)
97 whether or not this is an intentional design target. Similarly, the difficulty of flaking relatively
98 spherical cobbles (Toth, 1982) might bias initial clast selection and subsequent reduction toward
99 flat and elongated shapes even in the absence of explicit design targets. On the other hand, it has
100 been argued that the shape of Early Acheulean LFBs was intentionally predetermined using core
101 preparation techniques (Torre and Mora, 2018) and many researchers perceive efforts at inten-
102 tional shaping in the organization of flake scars on Early Acheulean handaxes and picks (Semaw
103 et al., 2009; Lepre et al., 2011; Beyene et al., 2013; Diez-Martín et al., 2015; Torre and Mora, 2018;
104 Duke et al., 2021). To date, however, the identification of Early Acheulean shaping has gener-
105 ally relied on qualitative assessment by lithic analysts. Such assessment may in fact be reliable,
106 but is subject to concerns about potential selectivity, bias, and/or overinterpretation (Davidson,
107 2002; Moore and Perston, 2016). Notably, a 3-dimensional morphometric (3DGM) study by Pres-
108 nyakova, et al. (2018) concluded that LCT shape variation in the Okote Member (~1.4 mya) at
109 Koobi Fora was largely driven by reduction intensity rather than different knapping strategies.
110 However, this study did not directly address the presence/absence of design targets constraining
111 the observed range of variation.

112 In later Acheulean contexts, reduction intensity effects are commonly equated with resharpening
113 and seen as an alternative to intentional form imposition (McPherron, 2000). Across
114 heavily-worked and relatively standardized LCT assemblages (e.g., Shipton and White, 2020),
115 a *lack* of association between morphology and reduction intensity has been used as an argument-
116 by-elimination for the presence of imposed morphological norms or “mental templates” (Ship-
117 ton and Clarkson, 2015a; García-Medrano et al., 2019; Shipton et al., 2023). However, in the
118 less heavily-worked and more heterogeneous assemblages typical of the early Acheulean (Kuhn,
119 2021), it is equally plausible that increasing reduction intensity would reflect degree of primary
120 reduction rather than subsequent resharpening (Archer and Braun, 2010). In this case, reduction
121 intensity effects on morphology would have the opposite interpretation: more reduction should
122 result in closer approximation of a desired form if such were present. For example, Beyene, et
123 al. (2013) found that increasing flake scar counts were associated with increasing handaxe re-
124 finement through time at Konso, Ethiopia, which may reflect a more general trend in the African
125 Acheulean (Shipton, 2018).

126 Interpretive approaches address this quandary by “reading” the organization of scars on individ-
127 ual pieces to infer intent, but an adequate method to objectively quantify these insights has yet
128 to be developed. Current measures of reduction intensity, such as the scar density index (SDI)
129 (Clarkson, 2013), are designed to estimate total mass removed from a core and are reasonably ef-
130 fective (Lombao et al., 2023). However, mass removal was not the objective of Paleolithic flaking.
131 Indeed, knapping efficiency is usually conceived as generating an outcome while *minimizing*
132 required mass removal. This is true whether the desired outcome is a useful flake, a rejuvenated
133 edge, or a particular core morphology. In simple flake production, mass removed is probably
134 a good reflection of the completeness of exploitation (“exhaustion”) of cores and may have im-
135 plications for required skill (Toth, 1982; Pargeter et al., 2023) as well as raw material economy
136 (Shick, 1987; Reeves et al., 2021). However, in core shaping and resharpening, mass removal
137 would typically represent an energetic and raw material cost to be minimized, and might even
138 interfere with function (Key, 2019). Without further information, relationships between artifact
139 shape and reduction intensity are thus open to conflicting interpretations as evidence of inten-
140 tional design or its absence.

141 Li, et al. (2015) proposed a Flaked Area Index (FAI) as an alternative to SDI as a measure of reduc-
142 tion intensity, arguing that its validity is supported by an observed correlation ($r=0.424$) with SDI.

143 However, they also explain that “flaked area does not necessarily relate to the number of flake
 144 scars... a small number of large scars can produce a large area of scar coverage, and conversely,
 145 a large number of small scars can produce a small area of scar coverage.” (p. 6). We suggest that
 146 what FAI actually captures is the spatial extent modifications to the surface of a core. It is thus
 147 complementary to the measure of volume reduction provided by SDI and provides additional
 148 information to inform technological interpretations. For example, a correlation between FAI
 149 and artifact form without any effect of SDI would suggest a focus on “least-effort” shape imposi-
 150 tion whereas the opposite pattern would be consistent with relatively intense resharpening of
 151 spatially restricted areas on the core. A lack of shape correlation with either measure would be
 152 expected for simple debitage with no morphological targets whereas a strong correlation with
 153 both would indicate a highly “designed” form achieved through extensive morphological and
 154 volumetric transformation. (**Figure 1**) In the current study we thus considered SDI and FAI to-
 155 gether in order to evaluate evidence of intentional shaping in the early Acheulean of Gona.

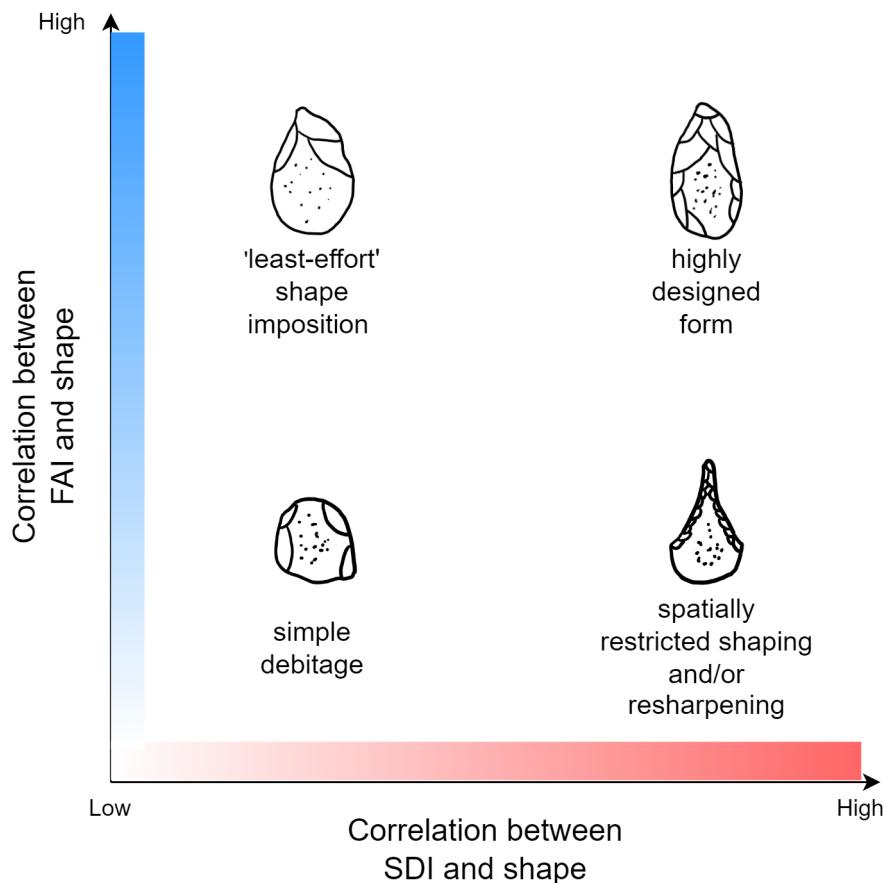


Figure 1: A conceptual model of inferring intention from artifact morphology.

156 **1.2 Measuring artifact form and modification**

157 Three-dimensional scanning and geometric morphometric (3DGM) methods are increasingly
158 common in the study of LCT form and reduction intensity (Lycett et al., 2006; Archer and Braun,
159 2010; Li et al., 2015, 2021; Shipton and Clarkson, 2015a; Presnyakova et al., 2018; Caruana, 2020).
160 These methods provide high-resolution, coordinate-based descriptions of artifact form includ-
161 ing detailed information about whole object geometric relations that is not captured by con-
162 ventional linear measures (Shott and Trail, 2010). This includes measures of surface area used
163 to compute both SDI and FAI measures (Clarkson, 2013; Li et al., 2015). At the time of writing,
164 however, 3D scans are available for only a small number of Gona artifacts, including 33 of the
165 Oldowan and Acheulean flaked pieces used in this study (Figure 2). Despite continuing improve-
166 ments, 3DGM methods still impose additional costs in terms of data collection and processing
167 time as well as required equipment, software, and training. Importantly, 3DGM methods cannot
168 be applied to pre-existing photographic and metric data sets (e.g., Marshall et al., 2002), includ-
169 ing available data from Gona. For this reason, and to better understand the relative costs and
170 benefits of 3DGM more generally, we sought to test the degree to which conventional measure-
171 ments can approximate 3DGM methods and produce reliable results by directly comparing our
172 conventional measures with 3DGM analysis of the 33 available scans.

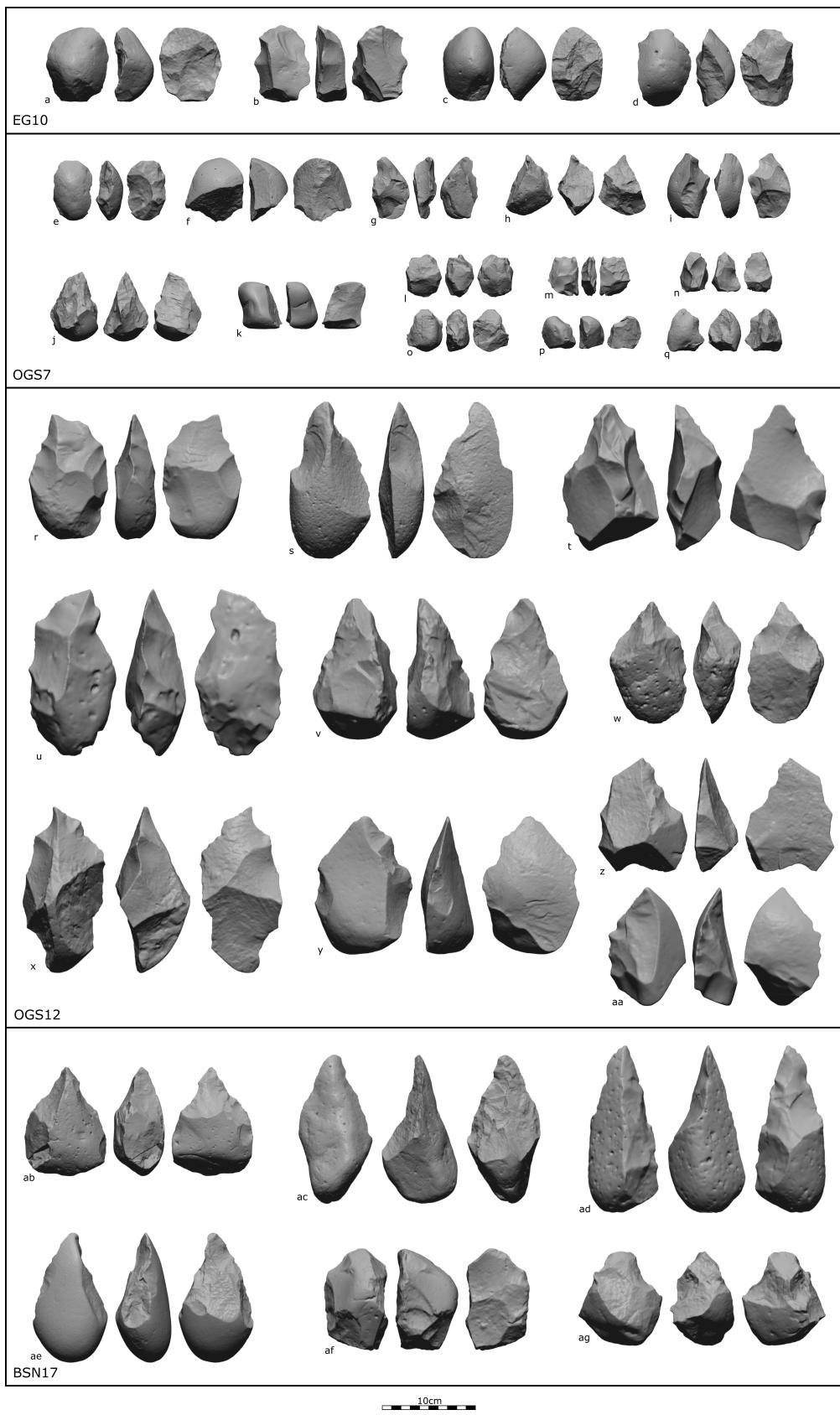


Figure 2: 3D Artifact scans from Gona used in this study.

173 For our study, we are specifically concerned with the accurate description of morphological vari-
174 ation and estimation of artifact surface and flaked areas. With respect to morphology, we were
175 encouraged by the fact that aspects of form variation relevant to our research question (i.e.,
176 core elongation, flattening, and pointedness) are relatively simple to describe using sparse data.
177 3DGM studies of LCTs collect vast amounts of shape data but may discard upward of 50% of the
178 observed variation in order to focus on two or three interpretable principal components. Across
179 studies, these PCs consistently correspond to basic features like elongation, relative thickness,
180 pointedness, and position of maximum thickness that also emerge from lower-resolution spatial
181 data (Lycett et al., 2006; Archer and Braun, 2010; García-Medrano et al., 2019) and studies em-
182 ploying linear measures rather than spatial coordinates (Crompton and Gowlett, 1993; Pargeter
183 et al., 2019). There is less evidence that conventional methods can accurately estimate artifact
184 surface and flaked areas. Clarkson (2013) advocated the use of 3D surface area measures as more
185 accurate than estimation from linear measures (e.g., surface area of a rectangular prism defined
186 by artifact dimensions). However, he also found that the error introduced by the linear approach
187 was a highly systematic, isometric overestimation of surface area and that results correlated with
188 direct 3D measures with an impressive $r^2 = 0.944$ and no effect of variation in core shape. Insofar
189 as it is variation in the relationship between surface area and flaking intensity that is of inter-
190 est, rather than absolute artifact size, such systematic overestimation may not be problematic.
191 Similar concerns apply to the estimation of flaked area. Traditionally, such estimates have been
192 done “by eye” as a percentage of the total artifact surface (e.g., Dibble et al., 2005). Such estima-
193 tions have been found to be reasonably accurate when compared to 3D methods, but with the
194 potential for substantial error on individual artifacts (Lin et al., 2010). The accuracy of by-eye
195 estimation has yet to be systematically studied in Early Stone Age cores like those from Gona.

196 1.3 The Early Acheulean at Gona

197 Early Acheulean sites in the Gona Project area (**Figure ??**) are distributed over a wide area within
198 the Dana Auole North (DAN), Ounda Gona South (OGS), and Busidima North (BSN) drainages in
199 the Busidima Formation (Quade et al., 2004) and range in age from approximately 1.7 to 1.2 mya
200 (Semaw et al., 2018). The specific sites included in the current analysis are DAN-5, OGS-5, OGS-
201 12, and BSN-17, all estimated to ca. 1.7 – 1.4 mya by stratigraphic position in the Gona sequence
202 (Quade et al., 2008; Semaw et al., 2020). The Busidima Formation accumulated through fluvial

203 deposition by the ancestral Awash River (Type I context) and its smaller tributary channels (Type
204 II context) (Quade et al., 2004, 2008). Oldowan sites at Gona all occur in Type I sediments, in-
205 dicating channel bank/margin (OGS-7) or proximal floodplain (EG-10, EG-12) contexts close to
206 the large, hetero-lithic clasts available from point bars in the axial river channel (Quade et al.,
207 2004; Stout et al., 2005). Acheulean sites continue to occur in Type I contexts (BSN-17, DAN-5)
208 but are also found in Type II sediments (OGS-5, OGS-12,) reflecting increased utilization of large
209 perennial tributaries to the ancestral Awash River (Quade et al., 2008). Clasts locally available in
210 these tributaries were relatively small, implying that the large flakes and cobbles used to produce
211 Acheulean artifacts were initially sourced from the axial river. A similar pattern of habitat diver-
212 sification and increasing lithic transport distances has been described at other sites and may
213 be typical of the early Acheulean (Hay, 1976; Rogers et al., 1994; Linares Matás and Yravedra,
214 2021). As with other early (i.e. >1.0 mya (Stout, 2011; Presnyakova et al., 2018)) Acheulean as-
215 semblages, the Gona collections include numerous “crudely made” handaxes and picks on large
216 flake blanks and cobbles, as well as large (> 10cm) unmodified flakes, flaked pieces interpreted
217 typo-technologically as Mode 1 cores (see Figure 1af), and smallerdebitage (Semaw et al., 2018;
218 Semaw et al., 2020).

219 2 Materials and Methods

220 2.1 Materials

221 2.1.1 Archaeological Sample

222 Artifact collections analyzed here include *in situ* pieces excavated from intact stratigraphic con-
223 texts and surface pieces systematically collected from the sediments eroding from these layers.
224 Surface pieces are included because the current technological analysis does not require more
225 precise spatial association, stratigraphic, and chronological control. Our sample comprises the
226 total collection of flaked pieces (Isaac and Isaac, 1997) and large (>10 cm) detached pieces from
227 each site, regardless of typo-technological interpretation.

²²⁸ **2.2 Methods**

²²⁹ **2.2.1 Artifact Classification**

²³⁰ Artifacts were classified according to initial form (pebble/cobble, detached piece, or indeterminate), presence/absence of retouch, technological interpretation (“Mode 1” core vs. “Mode 2” LCT), and archaeological context (Oldowan vs. Early Acheulean sites). LCTs were additionally classified as handaxes, knives, or picks following definitions from Kleindienst (1962). The validity of technological interpretations and typological classifications was assessed through cluster analysis based on artifact shape and reduction intensity variables.

²³⁶ **2.2.2 Artifact Measurement**

²³⁷ Conventional linear measures capture the direction (e.g., length > breadth) but not the location of geometric relations (e.g., position of maximum breadth). We address this by collecting linear measures defined by homologous semi-landmarks. All artifacts were oriented along their maximum dimension, which was measured and defined as “length”. The next largest dimension orthogonal to length was used to define the plane of “breadth”, with the dimension orthogonal to this plane defined as “thickness” Width (W_1, W_2, W_3) and thickness (T_1, T_2, T_3) measures were then collected at 25%, 50%, and 75% of length, oriented so that 25% Width > 75% Width.

²⁴⁴ To partition variation in shape from variation in size, we divided all linear measures by the geometric mean (Lycett et al., 2006). GM-transformed variables were then submitted to a Principal Components Analysis (covariance matrix) to identify the main dimensions of shape variation.

²⁴⁷ Our semi-landmark measurement system allowed us to improve on the prism-based surface area formula ($2LW + 2LT + 2 WT$) by using our 7 recorded dimensions to more tightly fit three prisms around the artifact: $SA = W_1T_1 + 2(.33L * W_1) + 2(.33L * T_1) + 2(.33L * W_2) + 2(.33L * T_2) + 2(.33L * W_3) + 2(.33L * T_3) + W_3T_3$. Surface area calculated in this way correlates with mass^{2/3} at $r^2 = 0.947$ in our sample. Calculated surface area was then used to derive the Scar Density Index: SDI = number of flake scars > 1cm per unit surface area (Clarkson, 2013; Shipton and Clarkson, 2015b). The Flaked Area Index (FAI: flaked area divided by total surface area)(Li et al., 2015) was estimated directly “by eye” as a percentage of the total artifact surface.

²⁵⁵ To assess the adequacy of shape descriptions based on our linear measures, we directly com-

256 pared these with shape as quantified by 3D methods on the 33 artifacts for which scans are avail-
257 able. GM-transformed linear measures from these 33 artifacts were submitted to a variance-
258 covariance matrix PCA. PCs with an eigenvalue greater than the mean were retained for analysis
259 and the results compared qualitatively (morphological interpretation of PCs) and quantitatively
260 (correlation of artifact factor scores) to 3D results. Accuracy of surface area and flaked area esti-
261 mates was also assessed by correlation with 3D results.

262 **2.2.3 3D Methods**

263 3DGM analysis was conducted using the *AGMT3-D* program of Herzlinger and Grosman (2018).
264 Artifacts were automatically oriented according to the axis of least asymmetry, then manually
265 oriented following the same orthogonal conventions described in section 2.3. Then, a grid of 200
266 homologous semi-landmarks were overlain on each artifact's surface. Generalized Procrustes
267 and Principal Component analyses were then undertaken to explore the shape variability of
268 the sample. The surface area of each artifact was calculated using the *Artifact3-D* program of
269 Grosman et al. (2022). *Artifact3-D* was also used to automatically identify the flake scar bound-
270aries and compute each scar's surface area, using the scar analysis functions of Richardson et al.
271 (2014).

272 **3 Results**

273 **3.1 Measurement Validation**

274 A PCA on GM transformed linear measures of the 33 artifacts identified two PCs accounting for
275 75.6% of the variance. Linear-PC1 (Eigenvalue = 0.189) explained 55.2% of the variance. Factor
276 loadings (**Table 1**) for Linear-PC1 reflect artifact elongation (i.e., an anti-correlation of length
277 vs. distal width and thickness). This A PCA on GM transformed linear measures the 33 arti-
278 facts identified two PCs accounting for 75.6% of the variance. Linear-PC1 (Eigenvalue = 0.189)
279 explained 55.2% of the variance. Factor loadings (**Table 1**) for Linear-PC1 reflect artifact elonga-
280 tion (i.e., an anti-correlation of length vs. distal width and thickness). This closely parallels the
281 length vs. width and thickness tradeoff captured by 3DGM-PC1 (**Figure 3**) and is reflected in a
282 tight correlation of artifact scores produced by the two PCs ($r = 0.903$, $p < 0.001$, **Figure 4A**). A sec-

Table 1: Component loadings for linear metric PCs on scanned sample.

Linear.metrics..GM.transformed.	Linear.PC1	Linear.PC2
Length	0.989	-0.107
W1	0.303	0.350
W2	0.403	0.767
W3	-0.176	0.790
T1	-0.135	-0.679
T2	-0.369	-0.623
T3	-0.607	-0.282

283 ond factor (Linear-PC2, eigenvalue = 0.07) explained an additional 20.4% of variance. This factor
 284 was less strongly correlated with its 3DGM counterpart (3DGM-PC2; $r = 0.344$, $p = 0.050$) prob-
 285 ably because Linear-PC2 describes anticorrelated variation in width and thickness (i.e., broad
 286 and flat vs. thick and pointed; **Table 1**) whereas 3DGM-PC2 more purely isolates convergence
 287 (**Figure 3**). The remainder of the shape variability explained by Linear-PC2 is captured by higher
 288 order 3DGM-PCs 3 through 5, which comprise the contribution of the left and right lateral mar-
 289 gins to relative thickness. Use of high-resolution, coordinate-based scan data thus generates
 290 PCs that identify more specific shape attributes, but the underlying morphological variability
 291 captured by the linear and 3D analyses remains similar. Together, 3DGM-PC2 ($r = 0.344$, $p =$
 292 0.050), 3DGM-PC3 ($r = -0.416$, $p = 0.016$), 3DGM-PC4 ($r = 0.458$, $p = 0.007$), and 3DGM-PC5 ($r =$
 293 -0.352 , $p = 0.044$) correlate well with Linear-PC2, cumulatively capturing whether the items are
 294 broad and flat or thick and pointed. A stepwise regression ($r^2=0.625$, $F(4,28)=11.697$, $p<0.001$,
 295 Probability-of-F-to-enter ≤ 0.050 ; Probability-of-F-to-remove ≥ 0.100) with Linear-PC2 as the
 296 dependent variable retained all four of these 3DGM-PCs as significant predictors.

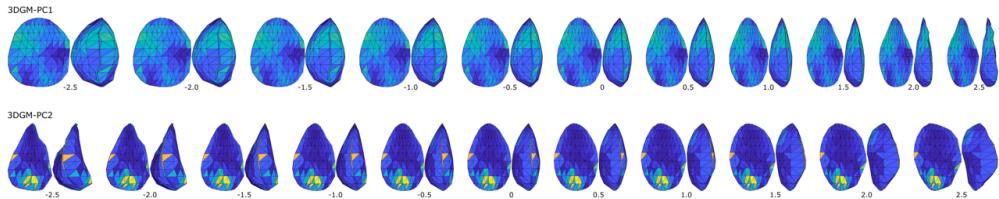


Figure 3: 3D models displaying the first two PCs.

Table 2: Component loadings for linear metric PCs in the full sample.

Linear.metrics..GM.transformed.	PC1	PC2
Length	0.905	-0.414
W1	0.635	0.299
W2	0.680	0.571
W3	0.486	0.761
T1	-0.510	-0.526
T2	-0.684	-0.525
T3	-0.719	0.023

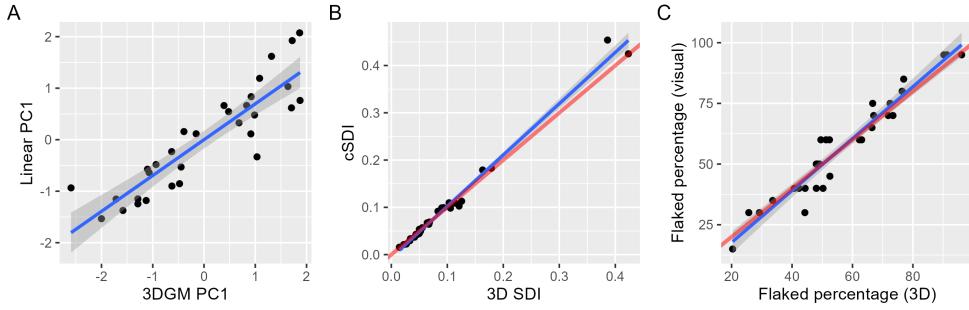


Figure 4: Comparison between linear measurement and 3d measurement.

297 We thus concluded that linear measures are adequate to capture relevant shape variation and
 298 proceeded with a PCA on our full sample. We identified two PCs accounting for 80.0% of the
 299 variance. PC1 (Eigenvalue = 0.216) explained 56.4% of the variance. Factor loadings (**Table 2**)
 300 for PC1 reflect artifact flatness (i.e., an anti-correlation of length and width vs. thickness) such
 301 that higher values indicate relatively thinner pieces. PC2 (Eigenvalue = 0.090) explained 23.6%
 302 of the variance. Factor loadings (**Table 2**) show that PC2 captures artifact convergence or “point-
 303 edness” (i.e., an anti-correlation of tip width with length and butt thickness) such that higher
 304 values indicate shorter, less pointed forms.

305 We also tested the validity of our two reduction measures, SDI and FAI. In agreement with Clark-
 306 son (2013), we found that surface area estimated from caliper measures displayed a strong corre-
 307 lation with ($r^2=0.975$, $p < 0.001$) but linear over-estimation of ($\beta = 1.58$) 3D surface area. This re-
 308 sults in a systematic underestimation of SDI that scales with core size. However, a simple correc-
 309 tion of the caliper estimate (dividing by the slope, 1.58) eliminates surface area over-estimation
 310 (mean difference = $256mm^2$ [$<1.7\%$ of mean], $p=0.040$) and produces SDI values that agree with
 311 3D values ($r^2=0.975$, $p < 0.001$, $\beta = 0.98$) (**Figure 4B**). We thus proceeded to apply this correction

312 to surface area estimates in the full sample. Insofar as these relationships are driven by basic
313 geometry, we expect these methods (including correction) to be generalizable to other ESA as-
314 semblages.

315 Visual estimation of flaked area approximated 3DGM measurement very closely ($r^2=0.932$, $p <$
316 0.001 , $\beta = 1.051$; **Figure 4C**) and without any systematic bias (paired t-test: mean difference =
317 -0.015% , 95% CI = 2.02% to 1.99% , $p = 0.987$). Individual errors ranged between -10.46% and
318 14.24% . We thus considered visual estimation to be reliable in our sample.

319 3.2 Classification Validation

320 We first conducted a stepwise DFA on all flaked pieces ($n=192$) with inferred technological Mode
321 (one vs. two) as the grouping variable and PCs 1 and 2, corrected SDI (cSDI), and FAI as the in-
322 dependent variables. All variables were retained, yielding one canonical DF (eigenvalue=1.825,
323 Wilks Lambda = 0.354, $p < 0.001$) which correctly classified 93.8% of artifacts. We thus accepted
324 the validity of classification by Mode in our sample and employed this distinction in subse-
325 quent analyses. There was no discernable difference in discriminant scores for Mode 1 cores
326 from Oldowan ($n=37$) vs. Acheulean ($n=39$) contexts (, $p = 0.746$). Mode 1 cores from Oldowan
327 contexts ($n=37$) do include 10 (27%) small, retouched flakes. Only one retouched flake from an
328 Acheulean context was classified by the DFA as a Mode 1 core. This piece, typologically classified
329 as a “knife”, is the smallest (93mm) retouched flake in the Acheulean sample. When retouched
330 flakes are excluded from the comparison, there are no significant differences in shape between
331 Mode 1 cores from Oldowan and Acheulean contexts. Interestingly, however, Acheulean Mode
332 1 cobble-cores are much larger (mean weight 480g vs. 186g, Cohen's $d=1.137$, $p < 0.001$) and less
333 heavily reduced (mean cSDI 0.057 vs. 0.103, Cohen's $d = -0.884$, $p < 0.001$) despite having similar
334 FAI (mean 0.52 vs. 0.46, Cohen's $d=0.271$, $p=0.266$).

335 Next, we conducted a stepwise DFA on all flaked Mode 2 pieces (i.e. excluding unmodified large
336 flakes, $n = 115$) with typology (handaxe, pick, knife) as the grouping variable and the same four
337 independent variables. Both shape PCs and FAI were retained, while cSDI was not entered. This
338 produced two DFs (DF1: Eigenvalue=1.536, 91.3% of variance; DF2: Eigenvalue = 0.146, 8.7% of
339 variance; Wilks Lambda = 0.344; $p < 0.001$) which correctly classified 71.3% of artifacts. Inspec-
340 tion of DF coefficients shows that DF1 captures an inverse correlation between flaked area and
341 pointedness (Linear-PC2) whereas DF2 captures a positive relationship between flaked area and

342 elongation (Linear-PC2). A bivariate plot (Figure 5) illustrates the fact that DF1 captures a range
343 of variation from pointed, heavily-worked picks, through handaxes, to knives, with substantial
344 overlap between adjacent types (Table 2). As an intermediate type, “handaxes” were correctly
345 classified only 43.9% of the time. In agreement with others (Presnyakova et al., 2018; Duke et al.,
346 2021; Kuhn, 2021) we conclude that these typological labels artificially partition a continuum of
347 variation and abandon them in subsequent analyses.

348 3.3 Effects of Reduction on Shape

349 To assess the influence of flake removals on core form, we examined the association between our
350 reduction measures (cSDI and FAI) and core shape (PC1, PC2). In the complete sample of flaked
351 pieces (n=192), we observed weak but significant effects of cSDI ($r=-0.294$, $p < 0.001$) and FAI
352 ($r=-0.294$, $p < 0.001$) on PC1(flatness) and of FAI only on PC2(pointedness) ($r=-0.436$, $p < 0.001$).
353 However, it is clear that these overall effects conflate different trends in Mode 1 vs. Mode 2 cores,
354 as well as in cores executed on flake vs. pebble/cobble bases. Within categories, we observed no
355 significant effects of cSDI whereas FAI had variable relationships with core form.

356 In Mode 1 cores, a weak negative effect of FAI on PC2(pointedness) ($n = 76$, $\beta = -0.006$, $r=0.240$,
357 $p = 0.037$) suggests that increasing extent of modification tends to slightly increase pointedness
358 (Figure 6a). No effects of FAI on PC1 (flatness) or of SDIc on either PC approach significance. FAI
359 and SDIc are moderately correlated ($\beta=0.001$, $r=0.524$, $p < 0.001$), an effect that reflects increases
360 in the upper limit of scar density values as flaked area increases (i.e., flaked area constrains max-
361 imum cSDI: Figure 6b).

362 In Mode 2 cores ($n=115$), reduction measures have different effects depending on initial blank
363 form. In general, the contrast between flat, lightly-worked flake bases and rounder, more-heavily
364 worked cobble bases tends to inflate relationships between FAI and core shape (Figure 5). Mode
365 2 cobble cores ($n=37$) display a negative effect of FAI on PC1(Flatness) ($\beta=-0.011$, $r=0.367$, $p =$
366 0.026), no effect of FAI on pointedness, and no association between FAI and cSDI ($r=0.141$, $p =$
367 0.406). Flake cores ($n=69$) show negative effects of FAI on PC1(Flatness) ($\beta=-0.007$, $r=0.284$, $p =$
368 0.018) and, more strongly, PC2(pointedness) ($\beta=-0.019$, $r=0.443$, $p < 0.001$). Comparison of Mode
369 2 flake cores with unmodified large flakes from Acheulean contexts ($n=35$) shows that ranges of
370 shape variation substantially overlap but that flaking generally reduces both PC1 and PC2. In
371 fact, regressions of PC1 and PC2 on FAI show y-intercepts that closely approximate unmodified

372 flake mean values (0.852 vs. 0.774 and 0.693 vs. 0.594, respectively) and significantly negative
 373 slopes as FAI increases (**Figure 6**). Flake cores show a small but significant positive effect of
 374 FAI on cSDI that, in contrast to Mode 1 cores, represents actual covariance rather than simply a
 375 relaxation of constraint (i.e. both upper and lower limits of cSDI increase with FAI).

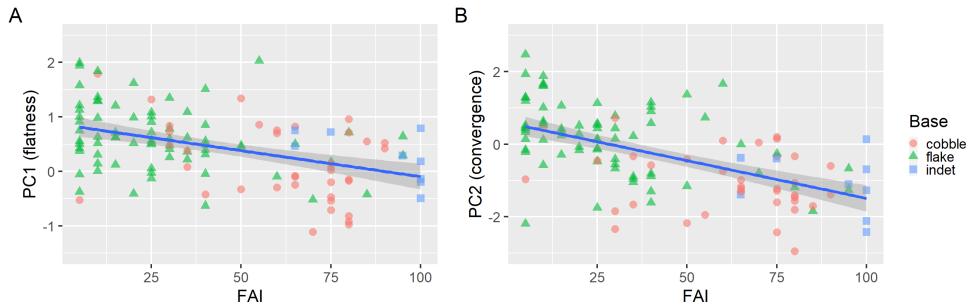


Figure 5: Mode 2 trends across blank types.

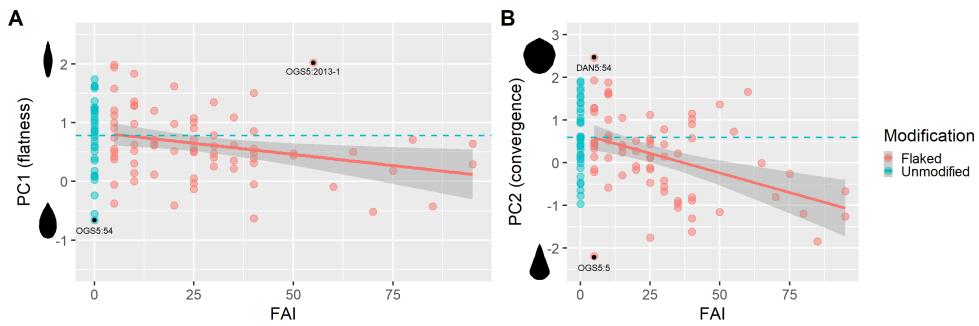


Figure 6: Effect of FAI compared to unmodified large flakes from Acheulean contexts.

376 A small number of Mode 2 cores (n=9) were so heavily modified (mean FAI=89%, range 65-100)
 377 that the blank form could not be determined. These heavily worked “indeterminate” cores tend
 378 to show similar PC1 (flatness) and PC2 (pointedness) values to cobble-base cores (i.e. thicker
 379 and more pointed than flake cores) and follow general trends of shape change with increasing
 380 FAI observed across base types (**Figure 5**).

381 4 Discussion

382 Our analyses of flaked pieces from Oldowan and Early Acheulean contexts at Gona support the
 383 presence of two distinct reduction modes (1 and 2) that can be reliably discriminated using mea-
 384 sures of artifact shape, flaking intensity, and extent of surface modification. However, they fail

385 to support further sub-division between conventional Mode 2 tool types (handaxe, pick, knife).
386 Following criteria proposed in the Introduction, we find strong evidence of imposed form in the
387 retouched large flakes from Acheulean contexts at Gona, weak evidence of shaping in Mode 2
388 cobble cores from Acheulean contexts, and little to no evidence of shaping in Mode 1 cores from
389 both Acheulean and Oldowan contexts. Our framing of this research question and its proposed
390 test criteria follows the preponderance of archaeological literature in conceptualizing artifact
391 design as a binary presence/absence of intentionally imposed form (Dibble et al., 2017). How-
392 ever, we will now argue that our results are better interpreted as reflecting variation in the de-
393 gree and nature of design expressed by ESA toolmakers. This shift in perspective recognizes that
394 the purposeful production of desired morphological and functional features can be achieved
395 by different combinations of raw material selection, blank production, and flaking strategies,
396 including the preservation of function through patterned changes in morphology (Kuhn, 2021).

397 4.1 Large Flakes

398 As we argued in the Introduction, the systematic production of large flakes indicates attention to
399 artifact size as a desired design feature. Many of these flakes would have possessed substantial
400 lengths of sharp edge and could have been immediately useful as cutting tools without further
401 retouch. In fact, 33% of the large flakes in our total sample are unretouched. Notably, this is also
402 true of the sub-sample from sites (OGS-5 and OGS-12) located in Type II, “tributary” sediments
403 (29 of 82 unmodified, 35%). This likely reflects transport and discard of unmodified flakes from
404 production sites closer to the axial river system sources of large clasts, consistent with the idea
405 that such flakes were themselves treated as useful tools. We consider the alternative possibility,
406 that unmodified flakes were unintended byproducts of local LCT production from transported
407 boulder cores, to be less likely considering the energetic inefficiency of this strategy as well as the
408 absence of large boulder cores in the assemblages (but see discussion of LCTs on cobble cores
409 below).

410 Whether or not unmodified flakes were themselves desired “end products”, a majority of large
411 flakes in the sample were retouched to some extent. Our analyses indicate that this flaking was
412 performed in a manner that produced systematic and directional shape changes. Specifically,
413 increasing FAI is associated with progressive reduction in relative breadth (increasing relative
414 thickness and elongation; PC1) and increasing convergence (PC2). In contrast, variation in cSDI

415 is not associated with artifact shape. These effects of surface modification extent but not re-
416 duction intensity indicate that it is the size and non-overlapping placement of flake removals
417 that drives directional shape change, rather than the removal of mass in general. The observed
418 correlation of cSDI with FAI further indicates that each new scar tends to remove additional un-
419 flaked area, consistent with the observed pattern of small numbers of relatively large and spa-
420 tially distributed flake removals. This clearly differs from classic re-sharpening models, which
421 emphasize shape change with decreasing artifact size as a byproduct of concentrated and re-
422 peated mass removal from particular areas of the artifact, such as working edges (Dibble, 1987;
423 McPherron, 2003). It also clearly differs from the expected effects of un-patterned debitage on
424 flake blanks, which does tend to increase relative thickness but also decreases elongation and is
425 not associated with convergence (Moore and Perston, 2016).

426 It is possible that the observed pattern reflects the intentional pursuit of an explicit morpholog-
427 ical target or “mental template.” This is generally seen as a strong claim implying rich mental
428 representation and manipulation of spatial features (Wynn, 2002), cultural mechanisms for the
429 intersubjective sharing of ideas of “appropriate” form (Wynn, 1995), and social reproduction of
430 the skills required to reliably achieve these forms (Liu et al., 2023). If there is such a target, how-
431 ever, it would seem to be a very loose one considering the observed range of shape variation in
432 retouched flakes (Figure 5). A more cognitively and culturally “lean” interpretation is that the
433 pattern reflects a procedural and/or functional bias toward establishing (or rejuvenating origi-
434 nal) cutting edges at one end of the long axis. In the absence of effective thinning and volume
435 management techniques, such a bias would naturally lead to narrowing/thickening of the piece
436 overall and especially at the “tip,” as is seen in our sample. This bias might itself be a socially
437 learned behavioral convention or “habit” (sensu Isaac, 1986), but could plausibly emerge di-
438 rectly from individual responses to the morphology of large flake blanks. Such flakes are typi-
439 cally elongated and thus present: 1) two longer edges along the maximum dimension that are
440 a natural focus for retouch, and 2) an ergonomic polarity defined by a thick (platform and per-
441 cussion bulb) “butt” vs. a feather terminated “tip” (cf. Key et al., 2016; Wynn and Gowlett, 2018).
442 Even with this minimal interpretation, however, we would argue that LFB flaking strategies at
443 Gona present evidence of design in the sense of being intended to produce and/or maintain de-
444 sired functional features of the LCT. This contrasts with patterns observed in cores classified as
445 Mode 1 in our analyses which, as expected, appear to reflect simple debitage without intended
446 morphological targets.

447 **4.2 Mode 1 Cores**

448 A Discriminant Function Analysis strongly supported the presence of two distinct morpholog-
449 ical types in our sample (based on overall shape and flake scar characteristics), which we had
450 previously typo-technologically interpreted as reflecting Mode 1 (debitage) and 2 (façonnage)
451 flaking strategies. Consistent with this interpretation, cores assigned to Mode 1 showed little or
452 no evidence of core shape management. One potential exception is an unexpected tendency of
453 increasing FAI to be associated with increasing convergence. However, this effect is an order of
454 magnitude weaker than that seen in LFB Acheulean cores and may be an artifact of our orient-
455 ing protocol, which aligns cores such that width at 25% length is always less than width at 75%
456 length. If reduction tends to increase asymmetry from initially rounded cobble forms, this could
457 account for the weak convergence effect we observe. In support of this interpretation, Mode 1
458 cores display a relatively strong correlation between FAI and cSDI driven by an increase in the
459 upper bound of cSDI values as FAI increases. In other words, we find that greater flaked area
460 on Mode 1 cores can, but does not necessarily, accommodate a greater number of flake scars.
461 This is what would be expected from knapping unconstrained by any systematic core-shaping
462 strategy.

463 The presence (n=14) of relatively large (> 100mm) Mode 1 cores at Gona Acheulean sites raises
464 the further possibility that at least some of these might be depleted cores from LFB production.
465 However, none of these display scars > 90mm (mean = 51.8 mm), most are very lightly reduced
466 (mean = 5.7 scars), and none meet the 150mm length cut-off used by Sharon (2009) to identify
467 “large” cores suitable for LFB production. The largest Mode I core in our sample is 137 mm long,
468 has five scars ranging from 25- 85 mm long, and an FAI of 25%. We thus consider it unlikely
469 that large Mode I cores from Acheulean contexts were used for LFB production. The behavioral
470 significance of relatively large, lightly-worked Mode 1 cores in Acheulean contexts is a question
471 for future research.

472 **4.3 Mode 2 Cores**

473 Our most complicated results come from Mode 2 cobble cores. Evidence of intentional shaping
474 is limited: FAI has a moderate effect on PC1 such that increasing flaked area produces relatively
475 shorter, thicker, and narrower pieces. This violates expectations that intentional LCT shaping

476 should increase elongation and convergence. However, it also fails to align with a reported ten-
477 dency for un-patterned debitage to decrease the thickness and increase the elongation of cobble
478 cores (Moore & Perston, 2016). This may reflect the fact that Mode 2 cobble cores at Gona begin
479 and remain relatively elongated (Table 3: mean L/W = 1.68) throughout reduction compared to
480 starting (n=29, mean L/W = 1.29) and ending (mean L/W = 1.34) cobble cores in the experiment
481 of Moore and Perston (2016). The moderate trend toward thickening and shortening of cores
482 with increasing FAI might plausibly be an effect of particularly elongated initial core form. In
483 the absence of intentional thinning techniques (Stout et al., 2014) flaking around the perime-
484 ter of an oblong core would be expected to preferentially reduce length and especially breath
485 (due to the long axis providing more potential platforms, especially if knappers seek to maxi-
486 mize flake size) while preserving thickness. Along these lines, Toth (1985) reported that “roller”
487 shaped cobbles tended to produce bifacial choppers in his unstructured debitage experiments.

488 Whether or not shaping occurred, it is clear that the elongated Mode 2 cobble cores at Gona do
489 provide evidence of initial size and shape selection within the range of rounded cobbles avail-
490 able from Type 1 channels in the Busidima Formation (Quade et al., 2004). This pattern is not
491 simply an analytical artifact of classifying elongated cores as “Mode 2” while selectively omitting
492 rounded forms: the complete sample of large (≥ 750 g) cores in our sample (n=25) is dominated
493 by relatively elongated forms (median L/W = 1.66). The small number (n=5) of large, rounded
494 (L/W < 1.33) cores in the sample are also anomalous in being very lightly worked compared to
495 more elongated large cores (mean scar count = 4.2 vs. 10.45, $p < 0.001$; mean cSDI = 0.14 vs. 0.31,
496 $p = 0.002$; mean FAI = 36 vs. 65, $p = 0.016$).

497 This could reflect the intentional selection of large, elongated blanks for LCT production, as
498 has been proposed at other early Acheulean sites (Harmand, 2009; Texier, 2018; Duke et al.,
499 2021). We would characterize such selection as a design choice even in the absence of subse-
500 quent shaping. However, large-cobble shape preferences might equally reflect biases related to
501 LFB production. Geometrically, elongated cobbles afford greater potential maximum dimen-
502 sions for detached flakes than do rounder cobbles of a similar mass. Flaking along the long axis
503 of elongated cobbles enables the production of elongated, side-struck flakes (Torre and Mora,
504 2018) that are typical of the LFB Acheulean and which provide longer and more ergonomic (cf.
505 Wynn and Gowlett, 2018) cutting edges than do round flakes. Flatter and more elongated cob-
506 bles are also generally easier to open and exploit (Toth, 1982; Whittaker, 1994; Texier, 2018).

507 This is an increasingly important consideration as size increases due to the increased percus-
508 sive force needed to detach larger flakes and the challenges of supporting and positioning larger
509 cores ([Semaw et al., 2009](#)), particularly with cobbles that are large but not sufficiently massive
510 to act as stationary targets for thrown hammerstones ([Toth and Schick, 2019](#)). We thus find it
511 plausible that at least some typological picks, handaxes, and knives made on cobble cores at
512 Gona could have been by-products of large flake production rather than intended forms. Toth
513 and Schick ([2019: 741](#)) similarly note that “heavily reduced boulder cores can assume the form
514 of smallish discoids and polyhedrons [and] may not be identified as sources of large flake blanks
515 by many archaeologists”. If this is true, such cores are distinguished from classic Mode 1 cores
516 by allometric effects on raw material choice and flake placement rather than a shift to deliberate
517 shaping.

518 The possibility that some Mode 2 cobble cores at Gona might be the remains of cores used for
519 large flake production was initially suggested by informal, “experiential” knapping with Gona
520 cobbles, during which attempts at LFB production produced pick-like forms as a byproduct.
521 Consistent with this hypothesis, the mean (152.9mm) and median (156mm) length of Mode 2
522 cobble cores are both above the 150mm cut-off proposed by Sharon ([2009](#)) and the maximum
523 scar length on each Mode 2 cobble core substantially overlaps with the size range of unmodified
524 large flakes (Table 3). Importantly, this is also true of the largest retouched flakes at Gona, nine
525 of which exhibit flake scars >100mm and thus could have been used as LFB cores. This possi-
526 bility has also been suggested at Koobi Fora ([Presnyakova et al., 2018](#)) and might be relevant to
527 understanding very large LCTs on flakes at other sites (e.g., [Beyene et al., 2013](#)).

528 Nevertheless, the fact remains that the preponderance of scars on large cobble cores are from
529 the removal of smaller flakes. Although these smaller scars could record preparatory flaking for
530 LFB predetermination ([Torre and Mora, 2018](#)) and/or a subsequent stage of small flake debitage
531 ([Shea, 2010](#)), it is difficult to rule out a role in shaping. Indeed, some pieces (e.g., Figure 1 ac,
532 ad, ae) exhibit delicate points and sharp edges that are strongly suggestive of intentional shap-
533 ing. If these pieces did in fact begin as cores for LFB production, it is possible that they were
534 subsequently shaped into cutting tools in their own right. Such lithic “upcycling” of depleted
535 LFB cores would help to explain the transport of these pieces away from the axial river system.
536 However, we should also be cautious not to overinterpret a small number of suggestive pieces
537 pulled from a wider range of variation, as they may simply represent low frequency “spandrels”

538 of un-structured debitage (Moore and Perston, 2016; Moore, 2020). These various possibilities
539 remain to be tested, but we note that there is no a priori reason to think that Acheulean tool
540 makers would have neglected potentially useful cores because they “belonged” to a particular
541 reduction sequence or technological type.

542 4.4 Implications

543 Early Acheulean technology is differentiated from the preceding Oldowan by changes in artifact
544 size as well as morphology (Isaac, 1977). However, discussion of the technological, cognitive,
545 and cultural implications of this transition has often focused on the emergence (or not) of inten-
546 tional shape imposition (Holloway, 1969; Isaac, 1976; Gowlett, 1986; Wynn, 1995, 2002; Roche,
547 2005; e.g., Duke et al., 2021). Our results suggest that this emphasis may be misplaced, and that
548 distinctive Early Acheulean artifact forms might represent secondary accommodations to the
549 primary goal of increasing tool size. From this perspective, Early Acheulean shape imposition is
550 best understood as reflecting an interaction between functional design goals and technological
551 constraints (Wynn and Gowlett, 2018; Kuhn, 2021).

552 The consensus view is that Oldowan flaking goals focused on the production of sharp, cutting
553 flakes through least effort debitage (Toth, 1985). Somewhat more controversially, Oldowan flak-
554 ing may have included preferred debitage patterns (Stout et al., 2019) and/or intentional core
555 maintenance and rejuvenation strategies (Delagnes and Roche, 2005). Our failure to find sys-
556 tematic effects of reduction on Oldowan core shape at Gona is consistent with this broad char-
557 acterization. Starting from this Oldowan baseline, the production of larger cutting tools could in
558 principle be achieved by increasing the size of cores and detached flakes and/or by attempting
559 to produce and maintain cutting edges on cores themselves rather than on the smaller pieces
560 detached from them. Both strategies are evident in the Early Acheulean at Gona.

561 At Gona, large flakes appear to have been transported across the landscape and discarded either
562 in their original form or after relatively light modification to impose desired cutting edges. This
563 behavior combines the two size-maximizing strategies identified above by increasing flake size
564 and then using these large detached pieces as supports for retouched edges. On the other hand,
565 large cobble cores at Gona display shape variation more consistent with debitage than shap-
566 ing. This leads us to suggest that these pieces might be depleted cores from large flake produc-
567 tion (size-maximizing strategy 1) that have been “upcycled” as large core tools (size-maximizing

568 strategy 2). In this way, the full range of artifact types and patterns of shape variation in the
569 Gona Early Acheulean can be parsimoniously accounted for as the expression of two strategies
570 for increasing cutting tool size.

571 This interpretation has three main implications. First, it supports the view that the Acheulean
572 initially emerged as a set of technological strategies for increasing cutting tool size, especially by
573 striking large flakes (Isaac, 1969). Hypothetically, this size increase might have been favored by
574 novel functional priorities, such as extended use-life, enhanced transportability, and utility for
575 heavy-duty cutting (Shea, 2010; Toth and Schick, 2019). It may also have been motivated and/or
576 enabled by increases in hominid body size. These overlapping possibilities appear likely to be
577 mutually reinforcing rather than mutually exclusive. In fact, the appearance of the Acheulean
578 starting 1.95 mya (Mussi et al., 2023) is roughly contemporaneous with an increase in the num-
579 ber, size, and ecogeographic range of stone tool sites in general (Plummer, 2004), as well as evi-
580 dence of habitat diversification and greater lithic transport distances for Acheulean sites specifi-
581 cally (Hay, 1976; Rogers et al., 1994; Quade et al., 2008; Torre et al., 2008), increasing emphasis on
582 large animal butchery (Linares Matás and Yravedra, 2021), and increases in hominid brain and
583 body size (Antón et al., 2014) including the first appearance of *Homo erectus* (Mussi et al., 2023).
584 Increased cutting tool size is a plausible response and/or enabling factor to many of these shifts
585 and is in that sense appears “overdetermined” by available evidence. Importantly, the current
586 study does not resolve the extent to which the production and transport of Early Acheulean tools
587 around the landscape (Presnyakova et al., 2018) occurred through planned logistical (Binford,
588 1980) activities of individuals and/or collaborating groups vs. the cumulative effects of indepen-
589 dent transport and recycling events over time (Reeves et al., 2023). Implications for planning
590 and prospection capacities (Szpunar et al., 2014) thus remain unclear.

591 Second, it reinforces a growing consensus (Presnyakova et al., 2018; e.g., Duke et al., 2021; Kuhn,
592 2021) that early Acheulean LCT types artificially partition a continuum of variation rather than
593 representing distinct target forms. More specifically, we propose that these forms emerge as
594 the expression of a generic goal of cutting tool size maximization implemented across vary-
595 ing material constraints and opportunities. This is particularly relevant to the interpretation
596 of “picks,” which have long been viewed as a morphologically distinct but functionally myste-
597 rious tool type. Toth and Schick (2019) note that picks do not appear designed to provide good
598 cutting edges but also do not show use-wear consistent with digging. This leads them to spec-

599 ulate that picks may have been specialized weapons used to dispatch large, wounded animals
600 with a blow to the head. However, picks are a common, persistent, and morphologically variable
601 artifact type in the Early Acheulean, which argues against such a narrow function. We suggest
602 that typological picks may lump together a variable mix of depleted LFB cores and large cutting
603 tools made on relatively thick (cobble or flake) blanks, possibly including upcycled LFB cores.
604 Within this interpretation, picks would be part of a continuum of morphological variation pro-
605 duced by different raw material forms and complex reduction histories, rather than a distinct
606 tool type designed for novel function. Due to such constraints, picks as a class may appear less
607 well designed for cutting than LCTs produced on thinner blanks. However, the relationship be-
608 tween tool morphology and cutting efficiency is complex and multivariate ([Key, 2016](#)), and the
609 relative utility of short and/or higher-angle edges on a more massive tool is not well understood
610 across diverse cutting tasks. Picks as an artifact class have not received the same attention as
611 handaxes and cleavers and we are unaware of any broad comparative synthesis. Beyene et al.
612 ([2013](#)) do report that picks at Konso are relatively conservative in shape and scar counts over a
613 period from 1.75-1.2 Ma during which associated handaxes show clear increases in refinement.
614 They thus suggest that pick function may already have been effectively optimized by 1.75-1.6 Ma
615 whereas the cutting function of handaxes continued to be enhanced. This is broadly consistent
616 with the current suggestion that typological picks identify a morphological extreme produced
617 by raw material features (esp. thickness) that constrain or discourage the refinement that might
618 be developed on other blanks. From 1.75-1.2 Ma, these ad hoc and/or less refined cutting tools
619 appear to have remained a stable element in the tool kit. However, they are nearly absent at 0.85
620 Ma, coincident with the appearance of “considerably refined” handaxes. Indeed, picks are not
621 commonly reported to co-occur with refined handaxes in later Acheulean contexts anywhere.
622 On a traditional functional interpretation, this would imply that their originally designed func-
623 tion also became less important in these contexts. The alternative possibility suggested here is
624 that increased investment in handaxe refinement decreased the perceived value of producing
625 and using ad hoc core tools for similar functions.

626 Lastly, our interpretation suggests that LCT variation at Gona probably does not reflect inten-
627 tional imposition of morphological norms (cf. [Holloway, 1969](#)) or detailed mental templates
628 ([Deetz, 1967](#)). Instead, we would focus attention on the cognitive and cultural implications of
629 size maximization strategies. As reviewed by Stout ([2011](#)), these stem from 1) the physical and
630 strategic challenges of quarrying large flakes and 2) the increased complexity of knapping action

631 hierarchies resulting from the addition of novel sub-goals (e.g. create a cutting edge) involved in
632 shaping large flake and cobble cores into useful tools. Systematic large flake production strate-
633 gies and techniques are qualitatively different from small-flake debitage (Isaac, 1969; Toth and
634 Schick, 2019) and thus add to the volume of technical knowledge and know-how that must be
635 acquired by individuals. This is directly relevant for inferring learning demands and the pos-
636 sible role of social support in Acheulean skill reproduction (Pargeter et al., 2019). Stout (2002)
637 provides a modern example of large flake production that illustrates the potential scope of such
638 demands. Interestingly, much earlier large flake production has been reported at the 3.3 Ma site
639 of Lomekwi 3 but is argued to be poorly controlled with minimal core reduction, numerous steps
640 and hinges, and extensive platform battering. Although concerns have been raised regarding the
641 dating and context of this site (Dominguez-Rodrigo and Alcalá, 2019; Archer et al., 2020), it may
642 provide an interesting technological comparison to Early Acheulean large flake production.

643 With respect to knapping action organization, the intentional placement of flake removals to
644 generate desired core morphologies demonstrates a more complex goal structure than is re-
645 quired for simple, least-effort debitage. Such complexity has implications for assessing cogni-
646 tive demands including relational integration, temporal abstraction, and goal abstraction (Stout,
647 2011). For this reason, our study was designed to address concerns that intentional shaping
648 might not actually be characteristic of Early Acheulean technology (e.g., Moore and Perston,
649 2016). We did find evidence for (at least) the imposition of cutting edges on LFBs, and offer
650 this a foundation for “minimum necessary competence” (*sensu* Killin and Pain, 2021) cognitive
651 interpretations. We remain agnostic as to whether similar knapping complexity was demon-
652 strated in the preceding Oldowan, but note that the rare and un-standardized (Gallotti, 2018)
653 occurrence of debitage on flakes prior to 2.0 mya does not provide evidence of intentional shap-
654 ing. Stout (2011) argued that elaborated small flake debitage methods contemporary with the
655 Early Acheulean, such as single platform Karari scrapers (Isaac and Isaac, 1997) and hierarchical
656 centripetal cores (Torre et al., 2003), document complex goal structures including the inten-
657 tional modification of the core morphology to enable subsequent flake detachments. Others
658 have seen evidence of such intentions in earlier bifacial (Duke et al., 2021) and unifacial (De-
659 lagnes and Roche, 2005) debitage strategies. However, all of these interpretations are based on
660 qualitative assessments of flake scar patterning and/or refitting and remain open to critique from
661 quantitative and experimentally-based approaches contending that similar knapping patterns
662 can emerge without “top down” intentions (Toth, 1985; Moore and Perston, 2016; Moore, 2020).

663 However these debates are eventually resolved, we would stress that the earliest demonstration
664 of a particular capacity is unlikely to represent its earliest presence. Logically, the minimum ca-
665 pacities required to support a novel behavior must be present before the behavioral innovation
666 can occur ([Stout and Hecht, 2023](#)) and may predate it substantially. We would thus argue that
667 technological innovation in the Early Acheulean was more likely stimulated by changing behav-
668 ioral and ecological strategies that placed a premium on cutting tool size, rather than by the
669 sudden emergence of new cognitive capacities. In this context, it is important to note that the
670 preponderance of cognitive and especially neuroarchaeological investigations of handaxe man-
671 ufacture ([Stout et al., 2008; Stout, 2011; Stout et al., 2015; Hecht et al., 2023](#)) have studied refined,
672 later Acheulean forms and should not be generalized to discussions regarding the emergence of
673 the Early Acheulean (cf. [Duke et al., 2021](#)). These neuroarchaeological studies were made pos-
674 sible by a robust understanding of the specific knapping behaviors being modeled ([Stout and](#)
675 [Hecht, 2023](#)). Similar studies modeling Early Acheulean technology are clearly needed and we
676 hope that investigations like the current one can help to provide the necessary behavioral foun-
677 dation.

678 4.5 Generalizability

679 It remains to be seen to what extent current results can be generalized to other Early Acheulean
680 sites. It is clear that LFB production as seen at Gona is typical ([Isaac, 1969](#)) of the African
681 Acheulean from its first known appearance ([Mussi et al., 2023](#)). Similarly, the transport and dis-
682 card of unmodified large flakes has also been reported at Peninj ([Torre et al., 2008](#)) and Koobi
683 Fora ([Presnyakova et al., 2018](#)) and may be more widespread than has been specifically noted in
684 publication. The general pattern of light, non-invasive retouch we observe also appears typical
685 of Early Acheulean sites (reviewed by [Presnyakova et al., 2018](#)). However, the effects of reduction
686 on LCT shape have not been systematically tested across sites in ways comparable to the current
687 analyses. This makes it difficult to determine if rare examples of “well shaped” Early Acheulean
688 LCTs (e.g., [Diez-Martín et al., 2019](#)) represent distinct technological behaviors or extreme points
689 along a continuum of variation. Presnyakova et al. ([2018](#)) argue for the latter, supported by shape
690 effects of reduction intensity identified using artifact size and edge angle as proxies. However,
691 these authors do not consider SDI or FAI and their analyses excluded any flaked pieces without
692 “clearly defined tips and bases,” thus limiting comparability with current results.

693 The occurrence of numerous large cobble cores (typological LCTs on cobble bases) at Gona is
694 atypical for East Africa and may reflect local raw materials availability. Kuman (2007) reports
695 that river cobbles from the nearby Blaaubank gravels are the dominant blank form in Gauteng
696 “Cradle of Humankind” Early Acheulean collections, possibly due to the rarity of larger boulder-
697 size clasts. Relatively high frequencies of LCTs on cobbles have also been reported from Gadeb
698 in Ethiopia (Torre, 2011). However, the large cobble cores at these sites have not been system-
699 atically studied as a distinct technological component or potential source of LFBs. Substantial
700 use of large slabs/blocks for LCT production has been reported at Kokiselei 4 (Harmand, 2009)
701 and Olduvai Gorge (Torre and Mora, 2005) but again it is not clear whether these could also have
702 been sources for LFBs during some part of their reduction sequence. Interestingly, Presnyakova
703 et al. (2018: Fig. 8) illustrate a boulder core with refitting large flake from FxJj65 that appears
704 to be comparable in size (~150mm long), shape ($L/W \approx 1.5$), and reduction intensity to some of
705 the more lightly worked cobble cores at Gona, providing at least anecdotal support for our in-
706 terpretations. In sum, however, systematic comparison across published Early Acheulean sites
707 is not currently possible due to differences in research questions, methods, and data reporting
708 practices. Clearly much work is needed to enable such comparison, but we do find some en-
709 couragement in the current finding that conventional linear measures, simple scar counts, and
710 visual flaked area estimations are sufficient to describe relevant variation in shape and reduction

711 5 Conclusion

712 Characteristic Early Acheulean artifact forms including large retouched flakes and core tools be-
713 gan to appear ca. 2.0 Ma (Mussi et al., 2023) as part of a pervasive ecological and behavioral shift
714 encompassing changing diet, ranging patterns, and habitat usage; increasing site frequency,
715 density, and ecogeographic distribution; and the first appearance of *Homo erectus*. Although
716 the cognitive and cultural significance of this new lithic industry is often framed in terms of the
717 emergence of discrete tool types and/or intentionally imposed morphological norms, we find
718 little evidence at Gona to support this. Instead, we observe systematic patterns of raw material
719 selection and core surface modification organized around the production and maintenance of
720 useful cutting edges on large(r) supports. Such larger cutting tools may have been prioritized
721 in newly emerging hominid behavioral adaptations due to their extended use-life, enhanced
722 transportability, and/or suitability for heavy-duty cutting.

723 This interpretation is consistent with a characterization of Early Acheulean tool forms as emerg-
724 ing from a set of “design imperatives” for large hand-held cutting tools (Gowlett, 2006; Wynn and
725 Gowlett, 2018), specifically including elongation and ergonomic positioning of cutting edges
726 [[@key2016](#); [@keyIntegratingMechanicalErgonomic2016](#)]. Our results thus provide support for
727 the presence of imposed form in the broad theoretical sense developed by Kuhn (2021): not
728 as the realization of a “holographic model” in the mind of the maker, but rather as the out-
729 come of technological choices made in view of material constraints and affordances (Moore,
730 2020). To the extent that some, but not all (Muller et al., 2022), later Acheulean assemblages pro-
731 vide stronger evidence of normative form imposition (García-Medrano et al., 2019; Shipton and
732 White, 2020; Liu et al., 2023) this underlines the heterogeneity of lithic technologies subsumed
733 within the “Acheulean Industry” and argues for more context-specific approaches to evaluating
734 behavioral, cognitive, and cultural implications.

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