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

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2023-11-30

Contents

1 Introduction **2**
1.1 Identifying design . . . 2
1.2 Measuring artifact form and modification . . . 6
1.3 The Early Acheulean at Gona . . . 8

2 Materials and Methods **10**
2.1 Materials . . . 10
2.2 Methods . . . 10

3 Results **12**
3.1 Measurement Validation . . . 12
3.2 Classification Validation . . . 13
3.3 Effects of Reduction on Shape . . . 14

4 Discussion **16**
4.1 Large Flakes . . . 16
4.2 Mode 1 Cores . . . 18
4.3 Mode 2 Cores . . . 19
4.4 Implications . . . 21
4.5 Generalizability . . . 25

5 Conclusion **26**

References **27**

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1 Introduction

The imposition of intended form on artifacts has long been viewed as a watershed in human cognitive and cultural evolution and is most commonly associated with the emergence of "Large Cutting Tools" (LCTs) in the Early Acheulean (Holloway, 1969; Isaac, 1976; Kuhn, 2021). However, this interpretation of Acheulean LCTs as intentionally designed artifacts remains controversial. Alternative proposals range from the possibility that LCTs were unintended by-products of flake production (Moore & Perston, 2016; Noble & Davidson, 1996) to the suggestion that their form was "at least partly under genetic control" (Corbey et al., 2016). Even accepting that LCT form was to some extent intended, there is substantial disagreement over the specificity of design. Some analyses have indicated that shape variation in Acheulean handaxes is largely a result of resharpening (Iovita & McPherron, 2011; McPherron, 2000) whereas others find form to be unrelated to reduction intensity and more likely to reflect normative expectations of what handaxes should look like (García-Medrano et al., 2019; Shipton & Clarkson, 2015b; Shipton & White, 2020). Such debates about shape of Acheulean LCTs may appear narrowly technical but have broad relevance for evolutionary questions including the origins of human culture (Corbey et al., 2016; Shipton & Clarkson, 2015b; Tennie et al., 2017), language (Stout & Chaminade, 2012), teaching (Gärdenfors & Högberg, 2017), brain structure (Erin E. Hecht et al., 2015), and cognition (Stout et al., 2015; Wynn & Coolidge, 2016). To examine these questions, we studied the complete collection of Early Acheulean flaked pieces from 5 sites at Gona Project Area and compared them with Oldowan cores from 2 published sites at Gona. By comparing shape variation to measures of flaking intensity and patterning, we sought to identify technological patterns that might reveal intent.

1.1 Identifying design

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

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

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

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

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

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

Li, et al. (2015) proposed a Flaked Area Index (FAI) as an alternative to SDI as a measure of reduction intensity, arguing that its validity is supported by an observed correlation (r=0.424) with SDI. However, they also explain that "flaked area does not necessarily relate to the number of flake scars...a small number of large scars can produce a large area of scar coverage, and conversely, a large number of small scars can produce a small area of scar coverage." (p. 6). We suggest that what FAI actually captures is the spatial extent modifications to the surface of a core. It is thus complementary to the measure of volume reduction provided by SDI and provides additional information to inform technological interpretations. For example, a correlation between FAI and artifact form without any effect of SDI would suggest a focus on "least-effort" shape imposition whereas the opposite pattern would be consistent with relatively intense resharpening of spatially restricted areas on the core. A lack of shape correlation with either measure would be expected for simple debitage with no morphological targets whereas a strong correlation with both would indicate a highly "designed" form achieved through extensive morphological and volumetric transformation. In the current study we thus considered SDI and FAI together in order to evaluate evidence of intentional shaping in the early Acheulean of Gona.

1.2 Measuring artifact form and modification

Three-dimensional scanning and geometric morphometric (3DGM) methods are increasingly common in the study of LCT form and reduction intensity (Archer & Braun, 2010; Caruana, 2020; Li et al., 2015, 2021; Lycett et al., 2006; Presnyakova et al., 2018; Shipton & Clarkson, 2015b). These methods provide high-resolution, coordinate-based descriptions of artifact form including detailed information about whole object geometric relations that is not captured by conventional linear measures (Shott & Trail, 2010). This includes measures of surface area used to compute both SDI and FAI measures (Clarkson, 2013; Li et al., 2015). At the time of writing, however, 3D scans are available for only a small number of Gona artifacts, including 33 of the Oldowan and Acheulean flaked pieces used in this study (**Figure** 1). Despite continuing improvements, 3DGM methods still impose additional costs in terms of data collection and processing time as well as required equipment, software, and training. Importantly, 3DGM methods cannot be applied to pre-existing photographic and metric data sets (e.g., Marshall et al., 2002), including available data from Gona. For this reason, and to better understand the relative costs and benefits of 3DGM more generally, we sought to test the degree to which conventional measurements can approximate 3DGM methods and produce reliable results by directly comparing our conventional measures with 3DGM analysis of the 33 available scans.

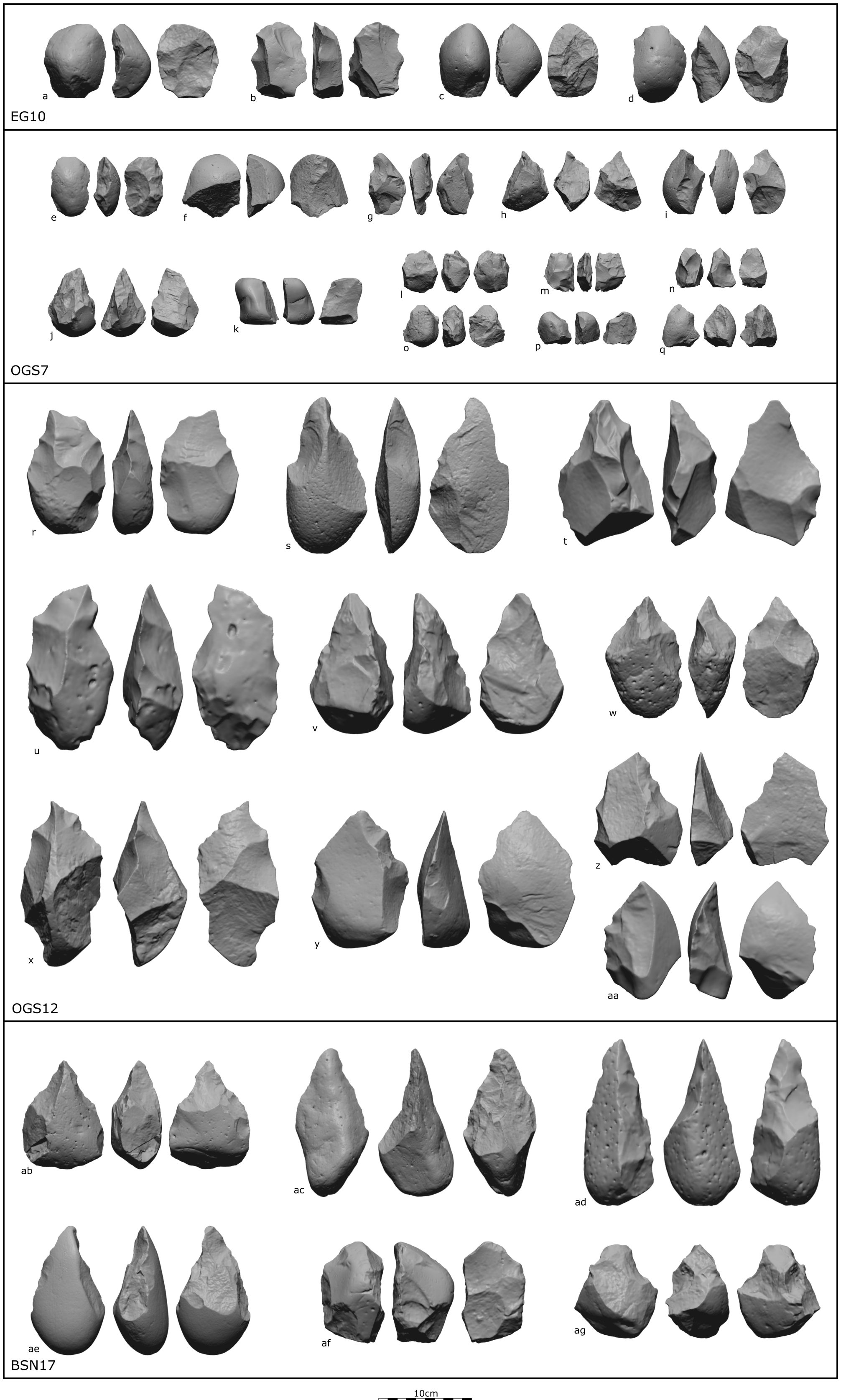

Figure 1: 3D Artifact scans from Gona used in this study.

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

1.3 The Early Acheulean at Gona

Early Acheulean sites in the Gona Project area (**Figure** 2) are distributed over a wide area within the Dana Aoule North (DAN), Ounda Gona South (OGS), and Busidima North (BSN) drainages in the Busidima Formation (Quade et al., 2004) and range in age from approximately 1.7 to 1.2 mya (Semaw et al., 2018). The specific sites included in the current analysis are DAN-5, OGS-5, OGS-12, and BSN-17, all estimated to ca. 1.7 – 1.4 mya by stratigraphic position in the Gona sequence (Quade et al., 2008; Semaw et al., 2020). The Busidima Formation accumulated through fluvial deposition by the ancestral Awash River (Type I context) and its smaller tributary channels

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

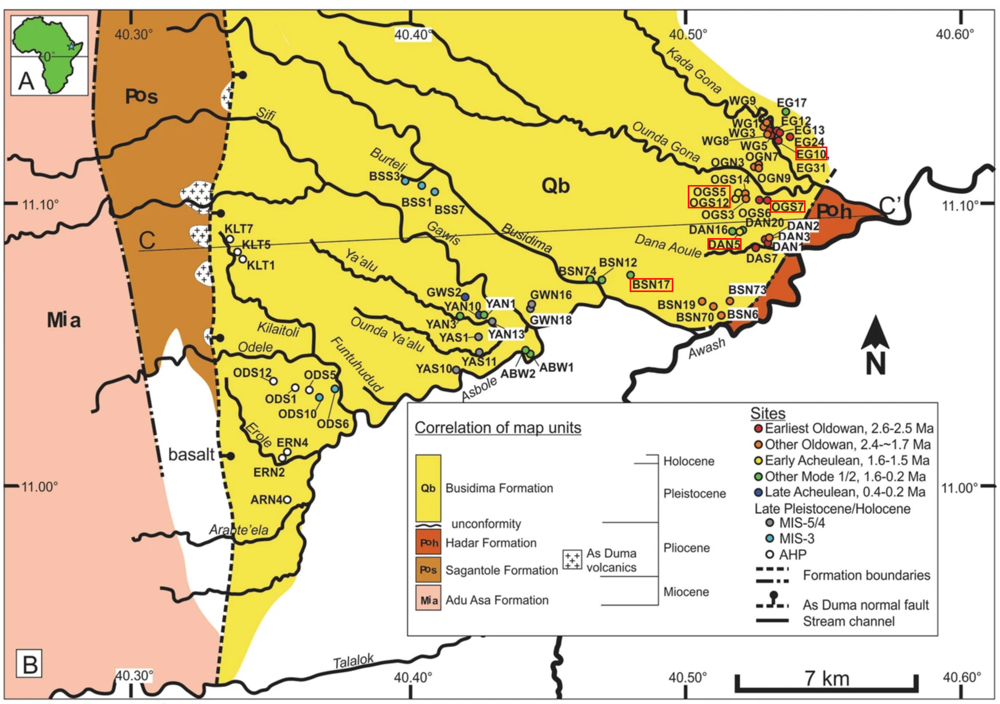

Figure 2: Gona site map.

2 Materials and Methods

2.1 Materials

2.1.1 Archaeological Sample

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

2.2 Methods

2.2.1 Artifact Classification

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.

2.2.2 Artifact Measurement

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. 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.

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 & Clarkson, 2015a). 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.

2.2.3 3D Methods

Artifact scans (N=33) were cleaned, smoothed, and re-meshed using MeshLab. The 3D triangular mesh of each scan was computed using Kazhdan and Hoppe's (2013) method of screened Poisson surface reconstruction in MeshLab. 3DGM analysis was conducted using the *AGMT3-D* program of Herzlinger and Grosman (2018). Artifacts were automatically oriented according to the axis of least asymmetry, then manually oriented in the interests of standardization with the length, width, and thickness dimensions defined by the longest axis, followed by the next two longest axes perpendicular to the first. The wider end of the artifacts was positioned as the proximal end (base), and more protruding surfaces were oriented towards the user in the first orthogonal view. Then, a grid of 200 homologous semi-landmarks were overlain on each artifact's surface. Generalized Procrustes and Principal Component analyses were then undertaken to explore the shape variability of the sample. The surface area of each artifact was calculated using the *Artifact3-D* program of Grosman et al. (2022). *Artifact3-D* was also used to automatically identify the flake scar boundaries and compute each scar's surface area, using the scar analysis functions of Richardson et al. (2014).

2.2.4 Analyses

Measurement Validation: To assess the adequacy of shape descriptions based on our linear measures, we directly compared these with shape as quantified by 3D methods on the 33 artifacts for which scans are available. GM-transformed linear measures from these 33 artifacts were submitted to a variance-covariance matrix PCA. PCs with an eigenvalue greater than the mean were retained for analysis and the results compared qualitatively (morphological interpretation of PCs) and quantitatively (correlation of artifact factor scores) to 3D results. Accuracy of surface area and flaked area estimates was also assessed by correlation with 3D results.

3 Results

3.1 Measurement Validation

A PCA on GM transformed linear measures the 33 artifacts identified two PCs accounting for 75.6% of the variance. Linear-PC1 (Eigenvalue = 0.189) explained 55.2% of the variance. Factor loadings (**Table** 1) for Linear-PC1 reflect artifact elongation (i.e., an anti-correlation of length vs. distal width and thickness). This A PCA on GM transformed linear measures the 33 artifacts identified two PCs accounting for 75.6% of the variance. Linear-PC1 (Eigenvalue = 0.189) explained 55.2% of the variance. Factor loadings (**Table** 1) for Linear-PC1 reflect artifact elongation (i.e., an anti-correlation of length vs. distal width and thickness). This closely parallels the length vs. width and thickness tradeoff captured by 3DGM-PC1 (Figure 3a) and is reflected in a tight correlation of artifact scores produced by the two PCs ($r = 0.903$, $p < 0.001$, Figure 3c). Comparison with conventional shape ratios (Table 2) similarly indicates that both Linear-PC1 and 3DGM-PC1 largely capture variation in artifact elongation. A second factor (Linear-PC2, eigenvalue = 0.07) explained an additional 20.4% of variance. This factor was less strongly correlated with its 3DGM counterpart (3DGM-PC2; $r = 0.344$, $p = 0.050$) probably because Linear-PC2 describes anticorrelated variation in width and thickness (i.e., broad and flat vs. thick and pointed; Table 1) whereas 3DGM-PC2 more purely isolates convergence (Figure 3a). The remainder of the shape variability explained by Linear-PC2 is captured by higher order 3DGM-PCs like 3DGM-PC3 to 5, which comprise the contribution of the left and right lateral margins to relative thickness. Use of high-resolution, coordinate-based scan data thus generates PCs that identify more specific shape attributes, but the underlying morphological variability captured by the linear and 3D analyses remains similar. Together, 3DGM-PC2 ($r = 0.344$, $p = 0.050$), 3DGM-PC3 ($r = -0.416$, $p = 0.016$), 3DGM-PC4 ($r = 0.458$, $p = 0.007$), and 3DGM-PC5 ($r = -0.352$, $p = 0.044$) correlate well with Linear-PC2 (Figure 3c), cumulatively capturing whether the items are broad and flat or thick and pointed. A stepwise regression ($r2=0.625$, $F(4,28)=11.697$, $p<0.001$, Probability-of-F-to-enter <= 0.050; Probability-of-F-to-remove >= 0.100) with Linear-PC2 as the dependent variable retained all four of these 3DGM-PCs as significant predictors.

Table 1: Component loadings for linear metric PCs .

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

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

We also tested the validity of our two reduction measures, SDI and FAI. In agreement with Clarkson (2013), we found that surface area estimated from caliper measures displayed a strong correlation with ($r2=0.975$, $p < 0.001$) but linear over-estimation of ($\beta = 1.58$) 3DGM surface area (Figure 4a). This results in a systematic underestimation of SDI that scales with core size (Figure 4b). However, a simple correction of the caliper estimate (dividing by the slope, 1.58) eliminates surface area over-estimation (mean difference = 256mm2 [<1.7% of mean], p=0.040) and produces SDI values that agree with 3DGM ($r2=0.975$, $p < 0.001$, $\beta = 0.98$) (Figure 4c). We thus proceeded to apply this correction to surface area estimates in the full sample. Insofar as these relationships are driven by basic geometry, we expect these methods (including correction) to be generalizable to other ESA assemblages.

3.2 Classification Validation

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

Next, we conducted a stepwise DFA on all flaked Mode 2 pieces (i.e. excluding unmodified large flakes, n = 115) with typology (handaxe, pick, knife) as the grouping variable and the same four independent variables. Both shape PCs and FAI were retained, while cSDI was not entered. This produced two DFs (DF1: Eigenvalue=1.536, 91.3% of variance; DF2: Eigenvalue = 0.146, 8.7% of variance; Wilks Lambda = 0.344; p<0.001) which correctly classified 71.3% of artifacts. Inspection of DF coefficients shows that DF1 captures an inverse correlation between flaked area and pointedness (Linear-PC2) whereas DF2 captures a positive relationship between flaked area and elongation (Linear-PC2). A bivariate plot (Figure 5) illustrates the fact that DF1 captures a range of variation from pointed, heavily-worked picks, through handaxes, to knives, with substantial overlap between adjacent types (Table 2). As an intermediate type, "handaxes" were correctly classified only 43.9% of the time. In agreement with others (Duke et al., 2021; Kuhn, 2021; Presnyakova et al., 2018) we conclude that these typological labels artificially partition a continuum of variation and abandon them in subsequent analyses.

3.3 Effects of Reduction on Shape

To assess the influence of flake removals on core form, we examined the association between our reduction measures (cSDI and FAI) and core shape (PC1, PC2). In the complete sample of flaked pieces (n=192), we observed weak but significant effects of cSDI (r=-0.294, p <0.001) and FAI (r=-0.294, p<0.001) on PC1(flatness) and of FAI only on PC2(pointedness) (r=-0.436, p<0.001).

However, it is clear that these overall effects conflate different trends in Mode 1 vs. Mode 2 cores, as well as in cores executed on flake vs. pebble/cobble bases. Within categories, we observed no significant effects of cSDI whereas FAI had variable relationships with core form.

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

In Mode 2 cores (n=115), reduction measures have different effects depending on initial blank form. In general, the contrast between flat, lightly-worked flake bases and rounder, more-heavily worked cobble bases tends to inflate relationships between FAI and core shape (Figure 7c,d). Mode 2 cobble cores (n=37) display a negative effect of FAI on PC1(Flatness) (β=-0.011, r=0.367, p = 0.026), no effect of FAI on pointedness, and no association between FAI and cSDI (r=0.141, p = 0.406). Flake cores (n=69) show negative effects of FAI on PC1(Flatness) (β=-0.007, r=0.284, p = 0.018) and, more strongly, PC2(pointedness) (β=-0.019, r=0.443, p < 0.001). Flake cores show a small but significant positive effect of FAI on cSDI that, in contrast to Mode 1 cores, represents actual covariance rather than simply a relaxation of constraint (i.e. both upper and lower limits of cSDI increase with FAI).

Comparison of Mode 2 flake cores with unmodified large flakes from Achuelean contexts (n=35) shows that ranges of shape variation substantially overlap but that flaking generally reduces both PC1(flatness) and PC2(pointedness). In fact, regressions of PC1 and PC2 on FAI show y-intercepts that closely approximate unmodified flake mean values (0.852 vs. 0.774 and 0.693 vs. 0.594, respectively) and significantly negative slopes as FAI increases (Figure 9).

A small number of Mode 2 cores (n=9) were so heavily modified (mean FAI=89%, range 65-100) that the blank form could not be determined. These heavily worked “indeterminate” cores tend to show similar PC1(flatness) and PC2(pointedness) values to cobble-base cores (i.e. thicker and more pointed than flake cores; Figure x). They also appear to follow general trends of shape change with increasing FAI observed across base types (Figure 10).

4 Discussion

Our analyses of flaked pieces from Oldowan and Early Acheulean contexts at Gona support the presence of two distinct reduction modes (1 and 2) that can be reliably discriminated using measures of artifact shape, flaking intensity, and extent of surface modification. However, they fail to support further sub-division between conventional Mode 2 tool types (handaxe, pick, knife). Following criteria proposed in the Introduction, we find strong evidence of imposed form in the retouched large flakes from Acheulean contexts at Gona, weak evidence of shaping in Mode 2 cobble cores from Acheulean contexts, and little to no evidence of shaping in Mode 1 cores from both Acheulean and Oldowan contexts. Our framing of this research question and its proposed test criteria follows the preponderance of archaeological literature in conceptualizing artifact design as a binary presence/absence of intentionally imposed form (Dibble et al., 2017). However, we will now argue that our results are better interpreted as reflecting variation in the degree and nature of design expressed by ESA toolmakers. This shift in perspective recognizes that the purposeful production of desired morphological and functional features can be achieved by different combinations of raw material selection, blank production, and flaking strategies, including the preservation of function through patterned changes in morphology (Kuhn, 2021).

4.1 Large Flakes

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

Whether or not unmodified flakes were themselves desired “end products”, a majority of large flakes in the sample were retouched to some extent. Our analyses indicate that this flaking was performed in a manner that produced systematic and directional shape changes. Specifically, increasing FAI is associated with progressive reduction in relative breadth (increasing relative thickness and elongation; PC1) and increasing convergence (PC2). In contrast, variation in cSDI is not associated with artifact shape. These effects of surface modification extent but not reduction intensity indicate that it is the size and non-overlapping placement of flake removals that drives directional shape change, rather than the removal of mass in general. The observed correlation of cSDI with FAI further indicates that each new scar tends to remove additional unflaked area, consistent with the observed pattern of small numbers of relatively large and spatially distributed flake removals. This clearly differs from classic re-sharpening models, which emphasize shape change with decreasing artifact size as a byproduct of concentrated and repeated mass removal from particular areas of the artifact, such a working edges (Dibble, 1987; McPherron, 2003). It also clearly differs from the expected effects of un-patterned debitage on flake blanks, which does tend to increase relative thickness but also decreases elongation and is not associated with convergence (Moore & Perston, 2016).

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

4.2 Mode 1 Cores

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

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

4.3 Mode 2 Cores

Our most complicated results come from Mode 2 cobble cores. Evidence of intentional shaping is limited: FAI has a moderate effect on PC1 such that increasing flaked area produces relatively shorter, thicker, and narrower pieces. This violates expectations that intentional LCT shaping should increase elongation and convergence. However, it also fails to align with a reported tendency for un-patterned debitage to decrease the thickness and increase the elongation of cobble cores (Moore & Perston, 2016). This may reflect the fact that Mode 2 cobble cores at Gona begin and remain relatively elongated (Table 3: mean L/W = 1.68) throughout reduction compared to starting (n=29, mean L/W = 1.29) and ending (mean L/W = 1.34) cobble cores in the experiment of Moore and Perston (2016). The moderate trend toward thickening and shortening of cores with increasing FAI might plausibly be an effect of particularly elongated initial core form. In the absence of intentional thinning techniques (Stout et al., 2014) flaking around the perimeter of an oblong core would be expected to preferentially reduce length and especially breath (due to the long axis providing more potential platforms, especially if knappers seek to maximize flake size) while preserving thickness. Along these lines, Toth (1985) reported that "roller" shaped cobbles tended to produce bifacial choppers in his unstructured debitage experiments.

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

This could reflect the intentional selection of large, elongated blanks for LCT production, as has been proposed at other early Acheulean sites (Duke et al., 2021; Harmand, 2009; Texier, 2018). We would characterize such selection as a design choice even in the absence of subsequent shaping. However, large-cobble shape preferences might equally reflect biases related to LFB production. Geometrically, elongated cobbles afford greater potential maximum dimensions for detached flakes than do rounder cobbles of a similar mass. Flaking along the long axis of elongated cobbles enables the production of elongated, side-struck flakes (Torre & Mora, 2018) that are typical of the LFB Acheulean and which provide longer and more ergonomic (cf. Wynn & Gowlett, 2018) cutting edges than do round flakes. Flatter and more elongated cobbles are also generally easier to open and exploit (Texier, 2018; Toth, 1982; Whittaker, 1994). This is an increasingly important consideration as size increases due to the increased percussive force needed to detach larger flakes and the challenges of supporting and positioning larger cores (Semaw et al., 2009), particularly with cobbles that are large but not sufficiently massive to act as stationary targets for thrown hammerstones (Toth & Schick, 2019). We thus find it plausible that at least some typological picks, handaxes, and knives made on cobble cores at Gona could have been by-products of large flake production rather than intended forms. Toth and Schick (2019: 741) similarly note that “heavily reduced boulder cores can assume the form of smallish discoids and polyhedrons [and] may not be identified as sources of large flake blanks by many archaeologists”. If this is true, such cores are distinguished from classic Mode 1 cores by allometric effects on raw material choice and flake placement rather than a shift to deliberate shaping.

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

Nevertheless, the fact remains that the preponderance of scars on large cobble cores are from the removal of smaller flakes. Although these smaller scars could record preparatory flaking for LFB predetermination (Torre & Mora, 2018) and/or a subsequent stage of small flake debitage (Shea, 2010), it is difficult to rule out a role in shaping. Indeed, some pieces (e.g., Figure 1 ac, ad, ae) exhibit delicate points and sharp edges that are strongly suggestive of intentional shaping. If these pieces did in fact begin as cores for LFB production, it is possible that they were subsequently shaped into cutting tools in their own right. Such lithic “upcycling” of depleted LFB cores would help to explain the transport of these pieces away from the axial river system. However, we should also be cautious not to overinterpret a small number of suggestive pieces pulled from a wider range of variation, as they may simply represent low frequency "spandrels" of un-structured debitage (Moore, 2020; Moore & Perston, 2016). These various possibilities remain to be tested, but we note that there is no a priori reason to think that Acheulean tool makers would have neglected potentially useful cores because they "belonged" to a particular reduction sequence or technological type.

4.4 Implications

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

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

At Gona, large flakes appear to have been transported across the landscape and discarded either in their original form or after relatively light modification to impose desired cutting edges. This behavior combines the two size-maximizing strategies identified above by increasing flake size and then using these large detached pieces as supports for retouched edges. On the other hand, large cobble cores at Gona display shape variation more consistent with debitage than shaping. This leads us to suggest that these pieces might be depleted cores from large flake production (size-maximizing strategy 1) that have been "upcycled" as large core tools (size-maximizing strategy 2). In this way, the full range of artifact types and patterns of shape variation in the Gona Early Acheulean can be parsimoniously accounted for as the expression of two strategies for increasing cutting tool size.

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

Second, it reinforces a growing consensus (e.g., Duke et al., 2021; Kuhn, 2021; Presnyakova et al., 2018) that early Acheulean LCT types artificially partition a continuum of variation rather than representing distinct target forms. More specifically, we propose that these forms emerge as the expression of a generic goal of cutting tool size maximization implemented across varying material constraints and opportunities. This is particularly relevant to the interpretation of "picks," which have long been viewed as a morphologically distinct but functionally mysterious tool type. Toth and Schick (2019) note that picks do not appear designed to provide good cutting edges but also do not show use-wear consistent with digging. This leads them to speculate that picks may have been specialized weapons used to dispatch large, wounded animals with a blow to the head. However, picks are a common, persistent, and morphologically variable artifact type in the Early Acheulean, which argues against such a narrow function. We suggest that typological picks may lump together a variable mix of depleted LFB cores and large cutting tools made on relatively thick (cobble or flake) blanks, possibly including upcycled LFB cores. Within this interpretation, picks would be part of a continuum of morphological variation produced by different raw material forms and complex reduction histories, rather than a distinct tool type designed for novel function. Due to such constraints, picks as a class may appear less well designed for cutting than LCTs produced on thinner blanks. However, the relationship between tool morphology and cutting efficiency is complex and multivariate (Key, 2016), and the relative utility of short and/or higher-angle edges on a more massive tool is not well understood across diverse cutting tasks. Picks as an artifact class have not received the same attention as handaxes and cleavers and we are unaware of any broad comparative synthesis. Beyene et al. (2013) do report that picks at Konso are relatively conservative in shape and scar counts over a period from 1.75-1.2 Ma during which associated handaxes show clear increases in refinement. They thus suggest that pick function may already have been effectively optimized by 1.75-1.6 Ma whereas the cutting function of handaxes continued to be enhanced. This is broadly consistent with the current suggestion that typological picks identify a morphological extreme produced by raw material features (esp. thickness) that constrain or discourage the refinement that might be developed on other blanks. From 1.75-1.2 Ma, these ad hoc and/or less refined cutting tools appear to have remained a stable element in the tool kit. However, they are nearly absent at 0.85 Ma, coincident with the appearance of "considerably refined" handaxes. Indeed, picks are not commonly reported to co-occur with refined handaxes in later Acheulean contexts anywhere. On a traditional functional interpretation, this would imply that their originally designed function also became less important in these contexts. The alternative possibility suggested here is that increased investment in handaxe refinement decreased the perceived value of producing and using ad hoc core tools for similar functions.

Lastly, our interpretation suggests that LCT variation at Gona probably does not reflect intentional imposition of morphological norms (cf. Holloway, 1969) or detailed mental templates (Deetz, 1967). Instead, we would focus attention on the cognitive and cultural implications of size maximization strategies. As reviewed by Stout (2011), these stem from 1) the physical and strategic challenges of quarrying large flakes and 2) the increased complexity of knapping action hierarchies resulting from the addition of novel sub-goals (e.g. create a cutting edge) involved in shaping large flake and cobble cores into useful tools. Systematic large flake production strategies and techniques are qualitatively different from small-flake debitage (Isaac, 1969; Toth & Schick, 2019) and thus add to the volume of technical knowledge and know-how that must be acquired by individuals. This is directly relevant for inferring learning demands and the possible role of social support in Acheulean skill reproduction (Pargeter et al., 2019). Stout (2002) provides a modern example of large flake production that illustrates the potential scope of such demands. Interestingly, much earlier large flake production has been reported at the 3.3 Ma site of Lomekwi 3 but is argued to be poorly controlled with minimal core reduction, numerous steps and hinges, and extensive platform battering. Although concerns have been raised regarding the dating and context of this site (Archer et al., 2020; Dominguez-Rodrigo & Alcalá, 2019), it may provide an interesting technological comparison to Early Acheulean large flake production.

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

However these debates are eventually resolved, we would stress that the earliest demonstration of a particular capacity is unlikely to represent its earliest presence. Logically, the minimum capacities required to support a novel behavior must be present before the behavioral innovation can occur (Stout & Hecht, 2023) and may predate it substantially. We would thus argue that technological innovation in the Early Acheulean was more likely stimulated by changing behavioral and ecological strategies that placed a premium on cutting tool size, rather than by the sudden emergence of new cognitive capacities. In this context, it is important to note that the preponderance of cognitive and especially neuroarchaeological investigations of handaxe manufacture (Erin Elisabeth Hecht et al., 2023; Stout et al., 2008; Stout, 2011; Stout et al., 2015) have studied refined, later Acheulean forms and should not be generalized to discussions regarding the emergence of the Early Acheulean (cf. Duke et al., 2021). These neuroarchaeological studies were made possible by a robust understanding of the specific knapping behaviors being modeled (Stout & Hecht, 2023). Similar studies modeling Early Acheulean technology are clearly needed and we hope that investigations like the current one can help to provide the necessary behavioral foundation.

4.5 Generalizability

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

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

5 Conclusion

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

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

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