



When less is more: risk, reward and optimisation in Acheulean handaxe manufacture and the impact of skill

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ABSTRACT

As the most numerous manifestations of technology across the Palaeolithic record, linking stone tool artefacts to past hominin cognition and expertise represents a major pursuit of human origins researchers. Acheulean handaxes are of special interest as the earliest tools with clear design modalities, along with their presence spanning major evolutionary events of the *Homo* genus between 1.8 and 0.2 million years ago. Prior knapping experiments have evidenced the prolonged learning-trajectories necessary when replicating later Acheulean biface forms, with novices producing characteristically thick, irregular and asymmetric tools, most similar to early Acheulean assemblages. Here, we track 88 handaxe reductions by expert and novice knappers, detailing discrepancies not only in their final configuration, but in their patterns of change across rough-out and finishing stages. Extensive flaking (past the rough-out stage) improved expert handaxes but led to an accumulation of knapping errors and edge degradation for novices, providing incentive for the latter to adopt conservative flaking strategies. Simply, novice knappers should stop earlier during handaxe-shaping sequences, to maintain working edges and minimise the opportunity for breakages, edge crushing, and other major errors. This scenario presents a conflict between the immediate goals of tool use and long-term trajectories in skill acquisition; risk-aversion can yield short-term benefits but will hinder expansion of the technological repertoire. We suggest that the expertise required to produce bifaces characteristic of the later Acheulean required a greater propensity to incur short-term costs whilst knapping, facilitating long-term benefits in skill development.

1. Introduction

1.1. Acheulean handaxe technology

The Acheulean has been framed as paradoxical (Lycett et al., 2016), showing unique stasis as a temporally and geographically expansive technocomplex, yet often defined by one of the most diverse tool categories of the Palaeolithic: the handaxe. While generalised as large ‘bifacially trimmed core tools’ with converging tips and globular butts (Wynn, 1995; Gowlett, 2006), an aurora of sub-classic Large Cutting Tools (LCTs) is recognised, encompassing broad variation in shaping method, *bauplan*, size and material (Isaac, 1977; Key, 2019; Kuhn, 2021). Some structure within this variation is apparent, with neighbouring and penecontemporaneous sites sharing more features (Vaughan, 2001; Lycett, 2009; Gowlett, 2015; Ashton and Davis, 2021; García-Medrano et al., 2023; Clark et al., 2024). The broadest purported

trend is between early and later iterations of the Acheulean, with younger assemblages typified by more intensively shaped and regularised handaxe forms (Moncel et al., 2015; Schick and Toth, 2017; Gallotti & Mussi 2017; Shipton, 2018). While unidirectional models of handaxe evolution have been disregarded, a distinction between ‘early’ and ‘late’ Acheulean forms remains popular, with the emergence of more complex biface knapping techniques inferred between 1 and 0.5 ma, across Africa (Shipton, 2018; Wilson and Caruana, 2024; Sánchez-Dehesa Galán et al., 2022; Mussi et al., 2023), West Asia (Jagher et al., 2015; Herzlinger et al., 2021a), and Europe (Stout et al., 2014; Antoine et al., 2016; Davis et al., 2021; García-Medrano et al., 2022a; García-Medrano et al., 2022b; Viallet et al., 2022). It is unclear whether invasively shaped handaxe forms typical of the later Acheulean represent multiple technological convergences or evidence of shared cultural information (Lycett and Gowlett, 2008; Mosquera et al., 2013; Moncel et al., 2016), although a ‘braided stream’ structure to later

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Acheulean culture suggests the latter (Key, 2022, 2024). Correspondence to the spread of post-*erectus* species – e.g. *H. heidelbergensis* – is frequently assumed (Ashton, 2015; Schreve et al., 2015; Mussi and Gallotti, 2017).

A shift in knapping skills is inferred from tool features including thin cross-sections, straight edges, and three-dimensional symmetry (Hutchence and Debackere, 2019; Pargeter et al., 2019; Caruana, 2020, 2021; Hicks, 2023; Muller et al., 2025). Late-stage fine-tuning of biface forms, as observed in these ‘late Acheulean’ handaxes, can be attributed to additional production steps, including platform preparation and the use of organic hammers for mid-volume thinning and edge trimming (Callahan, 1979; Whittaker, 1994). These steps are schematised as more elaborate action hierarchies, indicating greater demands on working memory (Stout et al., 2014; Gauchere, 2020; Paige and Perreault, 2024). In turn, increasing technological complexity in handaxes through time has been related to cognitive advancements in Middle Pleistocene *Homo* (Wynn, 2002; Stout, 2011) and more complex cumulative culture (Paige and Perreault, 2024).

1.2. Knapping skill and handaxe morphology

Experimental knapping studies, although unable to ‘re-run the past’ (Eren et al., 2016), help to contextualise the motor and cognitive demands of early and later Acheulean toolmaking, evidencing the methods and ease by which knappers control biface form. A consistent observation across knapping studies is the rapid learning curve for novices taught bifacial reduction, with most individuals able to produce simple biface forms after short practice sessions (Putt et al., 2014; Stade, 2017; Pargeter et al., 2019; Shipton, 2019; Torres and Preysler, 2020; Akhilesh et al., 2024). However, these are characterised by irregular and unstandardised forms, with the aforementioned fine-tuning associated with advanced learners. The largest (26 participants) and longest-running (up to 90 h) investigation of skill acquisition in handaxe technology by Pargeter et al. (2019) evidenced a plateau in biface scores (graded by trainer) by ~20 h of practice; projecting this line beyond the 90 h of tracked progress, they estimated it would take 225 h on average for participants to consistently produce handaxes meeting their idealised concept of late Acheulean technology. This is despite a learning context that may be near-optimal, as young adults with unlimited access to raw material and expert assistance. Studies of hammer force (Bril et al., 2010; Pargeter et al., 2024), trajectory (Rein et al., 2013), manual pressure (Williams-Hatala et al., 2021), and accuracy (Nonaka et al., 2010) has shown that novices are measurably worse at controlling knapping actions, creating more variable effects and expending greater energy. However, Torres & Preysler (2020) argue that it is not the incurring of errors that defines novices most of all, but their poor management of solutions. Mistakes – including edge crushing, step fractures, and flake overshoots – introduce higher risk for future removals and restrict options for tool configuration.

The errors and final handaxe forms typical of novice knapping are well detailed in prior studies but reduction trajectories are less understood, as are links between manufacturing decisions and functional perspectives. This is partly due to the conceptual framing of expertise, with inexperienced participants often understood through the lens of apprenticeship, as learners on a trajectory to becoming experts. From this perspective, knapping errors are a necessary obstacle which ultimately expands cause-and-effect knowledge. However, there is also clear value in understanding the relationship between expertise and handaxe functionality and the cost of errors, with less skilled hominins presumably also being tool users, interested in product efficiency. Important questions follow this reasoning: what procedural decisions are optimal to novices producing LCTs, and what short-term costs are implicit in the transition to ‘refined’ handaxe technology?

2. Method

2.1. Introduction

The experimental study was designed to test the effects of procedural knapping decisions on handaxe form, with handaxe morphology tracked from starting blank, to rough-out, to final form. These dynamics were compared between two broadly-defined skill levels, with 10 expert and 10 novice participants producing 80 finished handaxes in total (ethical approval granted by the Department of Archaeology Ethics Committee, University of Cambridge).

2.2. Participants

The 10 novice participants comprise a mixed-sex sample of young adults. Five individuals had no experience of flint knapping, whereas the other five reported 5–20 h of prior practice with expert tuition. Each novice was given 1 h of individual training by FS, comprising 15 min of demonstration and 45 min of guided practice, trialling all hammer types. Key concepts such as rough-out/finishing stages of reduction, alternate flaking, marginal/internal striking motions, and platform preparation were outlined, and participant questions were addressed. Guidance ceased once experiments had begun; broad concepts of knapping techniques could be reminded on request, but no advice was offered for the decisions in hand. The 10 participants comprising the expert group represented diverse backgrounds of experience, including professional craftspersons who coordinate workshops ($n = 6$), professors who engage with flintknapping for research and teaching ($n = 2$), and long-term hobbyists ($n = 2$). Experts were defined in this context as displaying the consistent ability to produce thin and invasively shaped handaxe forms. A large range of skill levels were represented, with some experts only recently accomplished in handaxe manufacture (~1 year of practice) and others skilled far beyond these means in biface production (>50 years). All experts were given the opportunity to practice with the percussors and materials prior to the experiment.

2.3. Materials

Each participant produced four handaxes from East Anglian (UK) spalled flint flakes, with adequate volume and breadth for handaxe production; on average, flakes measured 195 ± 23 mm by length, 150 ± 16 mm by width, and 63 ± 11 mm in thickness (Fig. 1). All flakes were 3D scanned using Artec Spider scanner prior to the study and randomly attributed to participants, including reserve stocks to account for any early breakages during knapping. Over the course of the experiment, each participant used quartzite, cortical flint, red deer antler and cattle bone hammers. Participants were provided with abraders they could optionally use to prepare striking platforms.

2.4. Tasks

Participants were asked to replicate a model (target) handaxe (Fig. 1) to the best of their abilities, focusing on the 3D shape of the model rather than its size, so long as they maintained a length of >10 cm; a threshold commonly used in LCT definitions (Wynn, 1995). Participants paused between the rough-out and finishing stages so handaxe rough-outs could be 3D scanned. This first rough-out phase was exclusively undertaken with quartzite hammerstones and was defined as ‘completed’ once a bifacial edge had been imposed around the circumference of the tool and participants deemed the bulk of the reduction complete. The rough-out stage was limited to hard hammer percussors, as is favoured for the removal of large flakes from irregular starting platforms (Newcomer, 1971; Whittaker, 1994). The second and final stage of handaxe reduction (‘finishing’) was undertaken by participants using either quartzite, cortical flint, antler or bone hammers, assigned to participants in a randomised order; this served another experimental goal to assess the

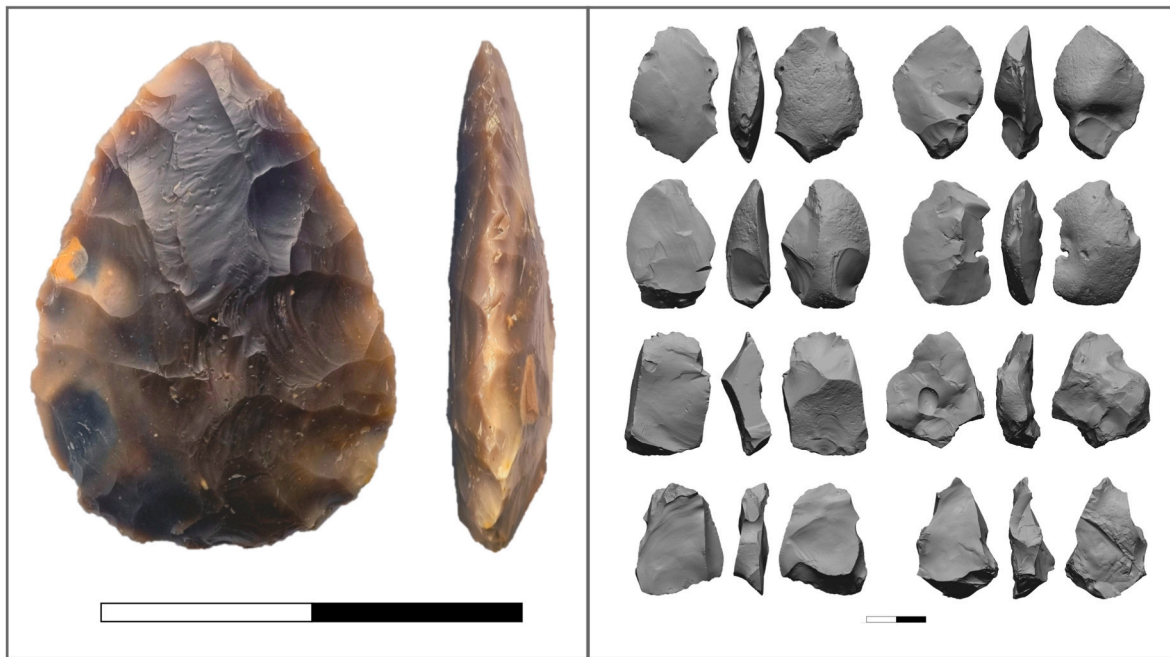


Fig. 1. The model handaxe (left) and a random sample of eight flakes used in the experiment (right); note variable form complexity, including squared edges and fossil inclusions. Scale bar equals 10 cm.

influence of percussor technology (see SI). All percussor types can be effective in late-stage bifacial reduction and are evidenced from Acheulean contexts (Wenban-Smith, 1989; Stout et al., 2014; Moigne et al., 2016; Bello et al., 2016). Flake blanks broken before the end of the rough-out stage were replaced, but handaxes broken during the final stage were not. All tasks were video recorded using a DSLR camera.

2.5. Analysis

The frequency and timings of failed hammer strikes and successful flake removals were recorded in seconds from the experiment footage. Abrasion and minor flaking (<20 mm) servicing platform preparation were not counted in the strikes category. In practice, these distinctions are difficult to implement, and minor errors are expected; however, this will be consistent across participants due to a single analyst (FS). 3D Models with an accuracy to 0.1 mm of the blanks, rough-outs, and finished handaxes were processed through AGMT3-D software developed by Herzlinger and Grosman (2018), producing Principle Component Analyses (PCA) from 5000 3D landmarks per tool and automated morphometric computations, including volume, length, width, thickness, edge sinuosity, bilateral and bifacial asymmetry. Sinuosity (described as section irregularity in AGMT3-D) is calculated in the software for each biface side separately, as the combined distance from outermost latitudinal coordinates on the Z axis from the line of best fit; sinuosity scores provided here present the mean from the two handaxe sides. All other metrics are as described in detail by Herzlinger and Grosman (2018). CEAM (Continuous Edge Angle Measurement) MATLAB code published by Muller et al. (2025) was used to measure edge angles, computed as the average angle triangulated from every coordinate on the outer 20 % of a tool's surface area around its entire circumference. Manual estimations of whole circumference (all circumferences were entirely flaked) and crushed circumference (*i.e.*, edge portions exhibiting battering) were also taken using a tape measure to the resolution of 1 mm. All statistical tests, as outlined in the results, were conducted through PAST v.5 (Hammer et al., 2001). Conservative (including non-parametric) statistical tests were chosen due to sample sizes and results discussed in text are extrapolated further in the SI. Model figures were produced through AGMT3D.

3. Results

3.1. Flaking sequence

Discounting pauses for scanning between rough-out and finishing phases, the average manufacturing duration was 22.8 min for experts and 20.8 min for novices. Experts had shorter intervals between strikes (mean = 7.0 s) than novices (mean = 10.4 s) and higher flaking success rates (expert = 61 %; novice = 48 %), with nearly double the number of flake removals on average (expert = 118; novice = 63) (Table 1). Regarding phasing, novices spent substantially longer on the rough-out stage (~9 min; 44 % of total time) compared to the experts (~6 min; 26 % of total time), who rapidly completed 'initial edging' and devoted more time to fine-tuning of biface form. Across both groups there is a decrease in flake success rate with time, visualised as summed histograms of frequency of flakes and mistrikes against time (Fig. 2). The frequency of mistrikes does not exceed the number of flakes removed at any stage for experts when averaged, but the proportion of failed blows typically passes 50 % of all strikes before termination the rough-out stage for novices. On average, 54 % of the final 20 strikes resulted in flakes for the experts, whilst only 32 % for the novices.

3.2. PCA results

In a PCA incorporating all rough-out and finished handaxes, PC1 (explaining 20.8 % of variation) represents a scale from thick and ovular forms (positive scores) to thin and triangular (negative scores) (Fig. 3). PC2 (12.5 % of variation) primarily encapsulates bifacial and bilateral regularity, with symmetric forms aligned around zero, and increasingly skewed planforms/profiles represented in positive and negative scores. The model handaxe is situated closely to zero on both axes, being highly symmetrical and cordiform. 30 Principal Components are necessary to characterise 90 % of total morphological variation (see SI). Monte Carlo permutations of means (*t*-test) and variation (*F*-test) show insignificant differences between novice and expert roughouts for PC1 ($p > 0.5$) and PC2 ($p > 0.3$), which occupy similar ellipses (90 % confidence), skewed towards positive PC1 values as relatively thick and ovular forms. The finished handaxes produced by experts have the lowest shape variation,

Table 1

Summary of flaking data showing the frequency of strikes and flakes (>2 cm) across stages and participant groups.

	Novice			Expert		
	Strikes	Flakes	Success Rate (%)	Strikes	Flakes	Success Rate (%)
Rough-out	60 ± 38	33 ± 15	60 ± 13	54 ± 26	41 ± 17	77 ± 13
Finishing	86 ± 53	31 ± 17	40 ± 17	143 ± 56	77 ± 35	55 ± 17
Total	146 ± 83	63 ± 28	48 ± 13	197 ± 61	118 ± 41	61 ± 14

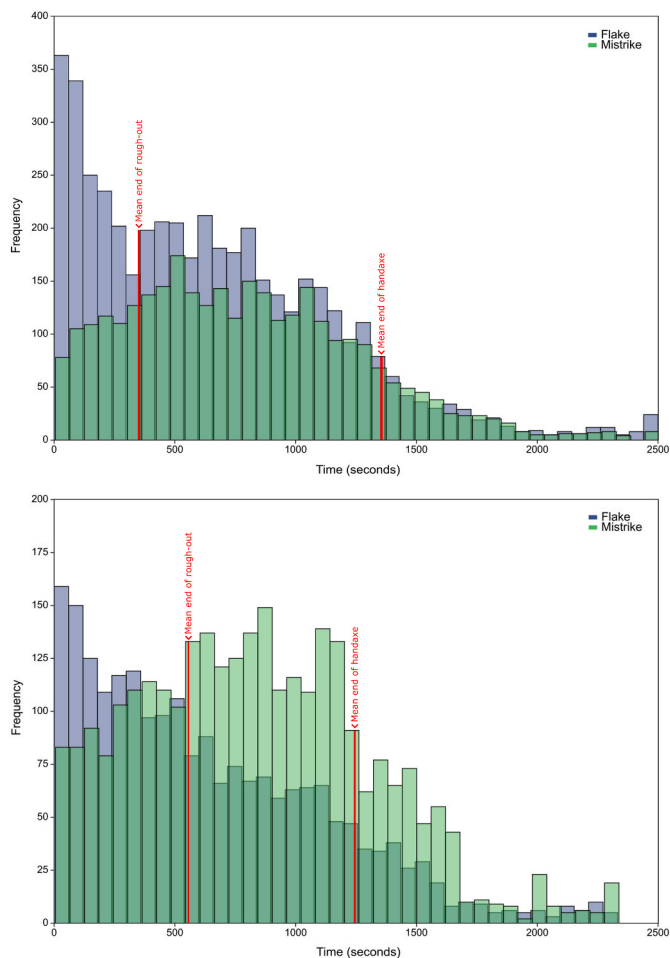


Fig. 2. Summed histograms showing frequency of successful and failed flake removals over 2500 s (approximately 42 min) within the novice (top) and expert (bottom) groups. First red lines represent mean end of rough-out stage and second lines denote mean finish times. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

with small ellipsis centred close to the model form; variation of this subset mostly relates to PC1, indicating that bifacial/bilateral symmetry is stable but there is more intragroup variation in planform and relative thickness (Fig. 3). Finished novice handaxes display similar diversity to the rough-outs but shift to an increased PC1 range and reduced PC2 range, indicating that forms become more regular in regards of symmetry and more diverse in planform and profile shapes (Fig. 3). This results in an average form close to the model handaxe, and thus also the expert handaxes, but with significantly greater intrasample variation for PC1 ($p = 0.041$) and PC2 ($p = 0.005$).

3.3. Handaxe reduction

Morphometric data from flake blanks, rough-outs and finished

handaxe scans provides insights into handaxe reduction and how these trends vary by knapping skill. For both experts and novices, roughing-out was more impactful on total morphology, bearing most of the change to size and shape from the original flake blank. This includes average (i.e., combined) decreases of 57 % in volume, 43 % in bilateral asymmetry, and 45 % in sinuosity, consistently more than double the change during the finishing stage (Table 2). While original flake blanks are statistically indistinguishable between experts and novices, there are significant discrepancies between the groups thereafter. Expert and novice rough-outs are significantly differentiated (Mann-Whitney U test, $p < 0.05$) by width/thickness and sinuosity, and finished handaxes are differentiated by all metrics except for axial length.

For experts, the finishing stage averagely improved bilateral symmetry by 26 %, bifacial symmetry by 21 %, and edge sinuosity by 25 %, from their former rough-out state. While the finishing stage is still beneficial for novices by most measures, improvements are significantly less; 12 %, 12 %, and 15 % respectively. Handaxe refinement (width/thickness) presents divergent trends, with refinement increasing steadily for experts (+12 %) but decreasing for novices (−9 %), thus transforming further from the model form. The finished novice handaxes are similar to the rough-outs produced by experts with regards to profile morphology, with bifacial asymmetry and sinuosity insignificantly differentiated in Mann-Whitney U tests ($p > 0.15$).

Differences in biface morphology metrics between rough-outs and finished handaxes can be investigated via linear regression (Fig. 4). No difference, and therefore no change, would plot along the identity line (slope = 1), represented here as a dashed grey line. Form improvements during late-stage reduction would fall below this threshold, while deterioration to handaxe form would plot above. Fig. 4 shows the plot for bilateral asymmetry, with the majority of points falling below the identity line for novices and experts, indicating consistent improvements to bilateral symmetry in the finishing stage, particularly for experts, with a trendline situated further from this threshold. The novice and expert trendlines are similar ($p = 0.665$) with slopes of 0.39 and 0.31 respectively indicating that rough-outs with low symmetry undergo greater change in this attribute over the final stage; however, this is not a flat regression, indicating that high bilateral asymmetry at the end of the rough-out stage has some effect on final form for novices ($r^2 = 0.179$, $p = 0.006$) and experts ($r^2 = 0.190$, $p = 0.005$).

Changes to edge sinuosity between rough-out and final stages present divergent patterns between experts and novices (Fig. 4). The novice handaxes present a clear positive correlation, with a slope of 0.78 ($r^2 = 0.508$, $p < 0.001$), marginally below the identity line; demonstrating a persistence of morphological features from the rough-out stage, with the finishing stage only contributing minor corrections to edge straightness. In contrast, a relatively flat (0.21) and insignificant ($r^2 = 0.007$, $p = 0.082$) correlation is exhibited by experts. A highly significant discrepancy between novice and expert trendlines ($p = 0.002$) indicates fundamental differences in reduction trajectories, with handaxe configurations during the rough-out stage having substantially less impact on final forms for experts. Irredeemable handaxe breakage (not attributed to internal flaws) was significantly higher (Chi²: 3.9; Fisher's exact p -value: 0.03) in the novice group, occurring 7 times during rough-out stage (leading to a restart with new blank) and 5 times during the finishing stage, comprising 26 % of all handaxe attempts (12/47). In contrast, this only occurred once during the rough-out stage and twice in the finishing stage for experts, defining only 7 % of handaxe attempts

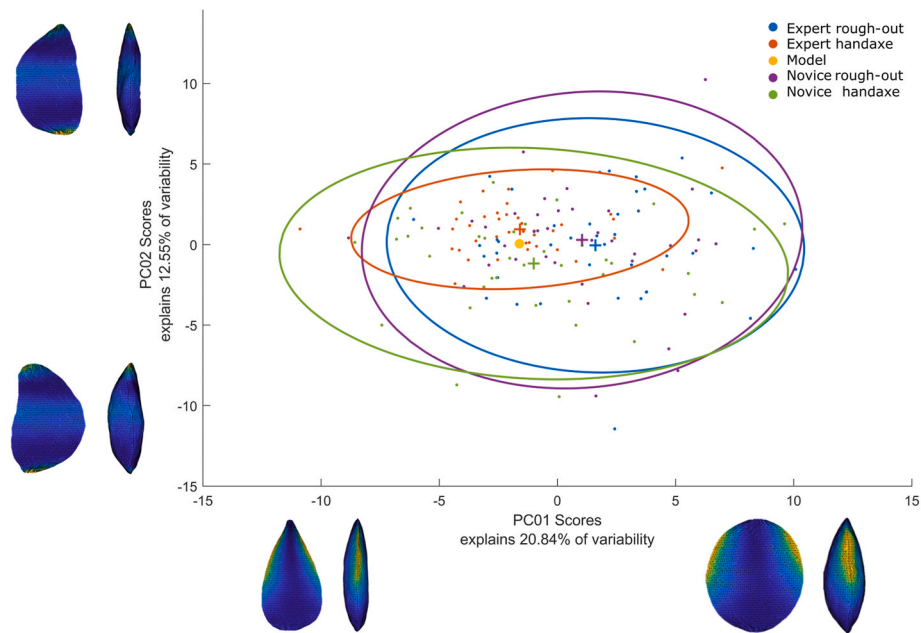


Fig. 3. PCA plot showing morphological variation within rough-out and finished handaxe samples. 3D meshes with heatmaps represent scales (+10 and -10) for each PC axis.

Table 2

Summary of change by key morphometric attributes across the three stages of reduction by group with percentages of change from original flake blank. Asterisks denote metrics that are significantly differentiated by group in Man-Whitney U tests.

	Novice				Expert			
	Flake	Rough-out	Finished	Total change	Flake	Rough-out	Finished	Total change
Volume	728964	301901	210292*		726310	324494	161763*	
		-58.6 %	-12.6 %	-71.2 %		-55.3 %	-22.4 %	-77.7 %
Length	194.40	150.63	132.79		193.25	155.94	130.07	
		-22.6 %	-9.1 %	-31.7 %		-19.3 %	-13.4 %	-32.7 %
Width/thickness	2.44	2.31*	2.21*		2.36	2.59*	2.65*	
		-5.4 %	-4 %	-9.4 %		+9.7 %	+2.2 %	+11.9 %
Bilateral asymmetry	17.46	9.93	7.89*		16.05	8.64	4.87*	
		-43.1 %	-11.7 %	-54.8 %		-43.3 %	-26.4 %	-69.7 %
Bifacial asymmetry	12.99	9.12	7.52*		12.61	7.14	4.45*	
		-29.8 %	-12.3 %	-42.1 %		-43.4 %	-21.3 %	-64.7 %
Edge sinuosity	298.60	185.72*	140.56*		305.84	148.19*	81.90*	
		-37.8 %	-15.1 %	-52.9 %		-51.5 %	-24.9 %	-76.4 %

(3/41).

3.4. Edge form

When comparing mean edge angles on the expert rough-outs and finished handaxes, no significant difference was present, with means of 79° in both instances, and close ranges across this reduction stage (Fig. 5A). Novice rough-outs have a larger range of edge angles than the experts, but the mean is comparable and insignificantly differentiated from the experts (p = 0.94) at 81°. However, there is a marked change from rough-out to finished handaxes by novices, with more obtuse angles observed in the final reduction stage. This shift is only of 5.5° on average, but the increase is consistent, with 90 % of novice handaxes increasing their mean edge angle from rough-out to final form (p < 0.001). The change may result from higher rates of battering in the final stage of handaxe reduction, increasing the obtuseness of the cutting edge apex. This explanation is supported by manual measurements of crushing along tool circumference, with a significant positive correlation between the ‘crushing index’ (crushed circumference/total circumference) with CEAM edge angle across both participant groups (r² = 0.35, p < 0.001) (Fig. 5B), and within groups (SI). Linear

regression between crushing index and flake success rate also presents a significant relationship in the novice group, with lower flake rates corresponding with higher crushing on final pieces (r² = 0.12, p = 0.029) (Fig. 5C). There is no significant relationship in the expert sample (r² < 0.01, p = 0.820); High (0.8) and low (0.2) flaking rates are both associated with low crushing scores. This indicates that failed strikes have different repercussions depending on skill, with experts able to minimise or reverse the effects of mistakes on edge morphology.

4. Discussion

4.1. Skill level and handaxe reduction

The present study contributes to well-established experimental evidence outlining the importance of expertise in handaxe reduction, with extensive experience usually necessary to consistently produce thin, symmetrical and straight-edged tools (Shelley, 1990; Geribàs et al., 2010; Pargeter et al., 2019; Lycett and Eren, 2019; Akhilesh et al., 2024). The results corroborate observations by Liu et al. (2023) that novices can exert greater control over handaxe planform than profile, finding it easier to reduce volume from the circumference than the

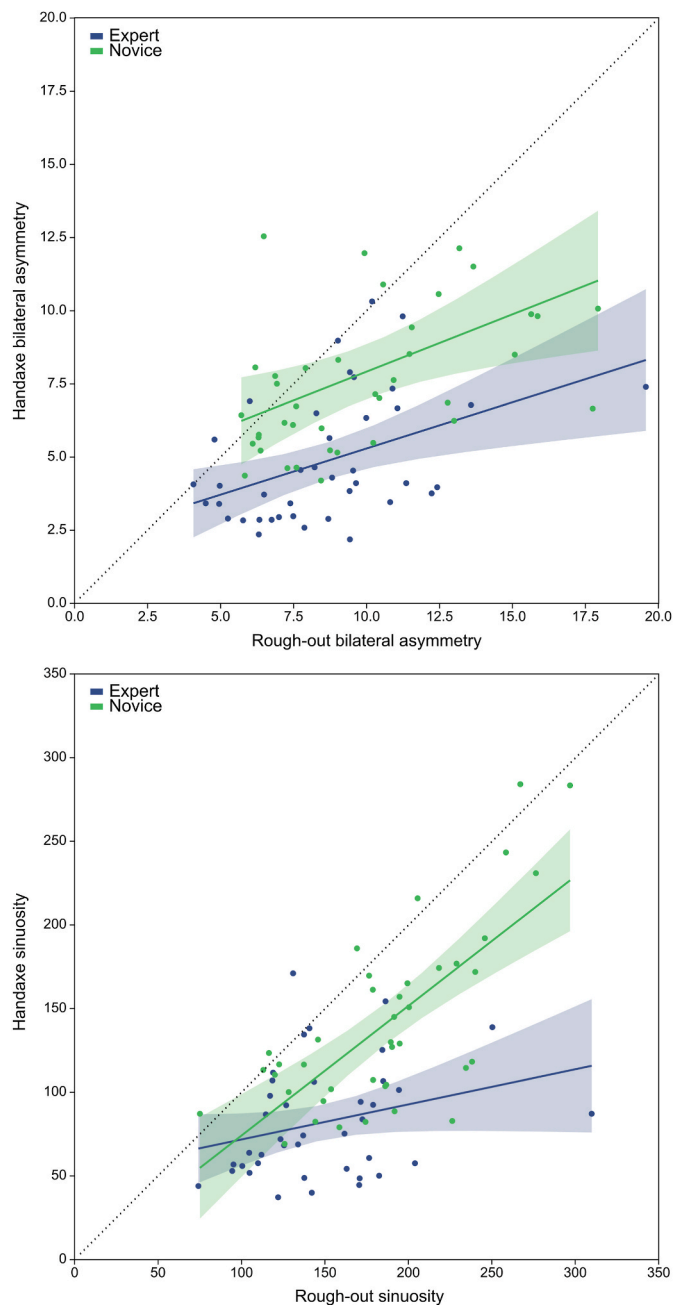


Fig. 4. Linear regressions showing relationship between bilateral asymmetry in rough-out and finished handaxe configurations (top) and sinuosity in rough-out and finished handaxes (bottom).

mid-portion. The decreasing width/thickness ratio of novice handaxes through reductions provides direct evidence supporting previous inferences that less experienced knappers struggle to thin bifaces; what expert knapper, Callahan (1979: 35), referred to as ‘Stage A Learning’, whereby tools ‘become relatively narrower and shorter without becoming relatively thinner’ yielding ‘Abbevillian-like bifaces’.

Morphometric data from all three reduction stages provides novel insight into knapping trajectories dependent upon skill, and a basis to infer the advantages and drawbacks of continued flaking following the initial establishment of a bifacial edge. Regarding 3D shape, novice handaxes are closer to the target form by the end of the finishing stage relative to the rough-out stage, with greater affinities to cordate planforms, higher symmetry, and less sinuous perimeters; the only divergence is in proportional thickness. While late-stage amelioration was

less than achieved by experts, this can be partly attributed to shorter reduction sequences. The main reason why knapping ceased earlier for novices appears to be the accumulation of errors at the edge apex, with successive mistrikes degrading the edge and making further flaking difficult. Edge crushing is approximately three times higher (~30 % of circumference) for novices at the end of the finishing stage than for experts, contributing to their higher average edge angles. While the flaking success rate also decreases for experts during reduction, this rarely drops below 50 % and there is no detectable effect on the final distribution of edge crushing, indicating that skilled knappers successfully mitigate the impact of mistrikes throughout reduction. The significant relationship between flaking rate and the extent of circumference crushing in the novice sample supports Torres and Preysler’s (2020: 902–903) observation that novices ‘do not solve their mistakes and repeatedly make their failures without changing their behaviour, generating an accumulation of effects (crushing, cascades, dulling) on the pieces’. Approximately one quarter of novice handaxe attempts terminated with breakage; nearly three times higher than the expert sample, providing the most extreme example of a detrimental outcome on tool-form resulting from continued and misjudged manufacturing choices.

4.2. Form and function

Relating morphological attributes to the efficiency of Large Cutting Tools is key to contextualising knapping strategies and what elements should be prioritised in tool manufacture. Key and Lycett (2017) undertook the largest experimental study to date testing form-function relationships, comprising a diverse sample of 500 handaxes. In their investigation, tool mass and 29 scale-free values characterising shape were correlated against the time taken for participants to cut through cardboard, rope and neoprene strips. The results indicate substantial independence of handaxe morphology from task efficiency under these conditions, with insignificant correlations between mass and shape across the whole sample and discrete correlations with mass at the extreme upper (>90 %) and lower (<10 %) sample bounds.

In the same study, the impact of edge sinuosity (in this case, irregular realised edge length divided by a straight-line measurement from tip to base) on handaxe performance was also investigated, revealing performance to decrease as edges became very irregular, at a ratio of 0.875–0.885, with little impact observed for variable measures above this threshold (Key, 2015). Given broad affordances in sinuosity and edge performance, this feature may be of low priority if further fine tuning is associated with additional risks. Key et al. (2015) later demonstrated edge angle (measured via calliper method) has a negative correlation with handaxe cutting performance up to ~70°, after which efficiency decreased, in part due to more obtuse edges increasing prehensile comfort in the ‘butt’ of the tools. The increased edge angles in novice handaxes, which appear to be related in part to edge crushing, would therefore have a negative impact on the creation of cutting stress by the working edges of tools, but be advantageous in terms of gripping comfort in a handaxe’s basal portion. Edge apex abrasion would likely also impact the sharpness of edges, with even minimal percussion-related crushing likely significantly reducing an edge’s capacity of cut efficiently (Key et al., 2019), evidencing the comparatively poor utility of the novice handaxes. The generation of partially detached micro debitage via crushing may have further practical considerations, with dislodged flake fragments posing a risk of ingestion if in food processing.

Considering these tested effects of handaxe shape and edge integrity on tool performance, it can be argued that a biface’s cutting edge has a more integral role in functionality than the broader morphology. Contextualised within the new experiment, this evidences an incentive for novices to cease handaxe reduction soon after a bifacial edge has been imposed, preventing the accumulation of knapping errors that could compromise sharpness and the acuteness of working edges. Any

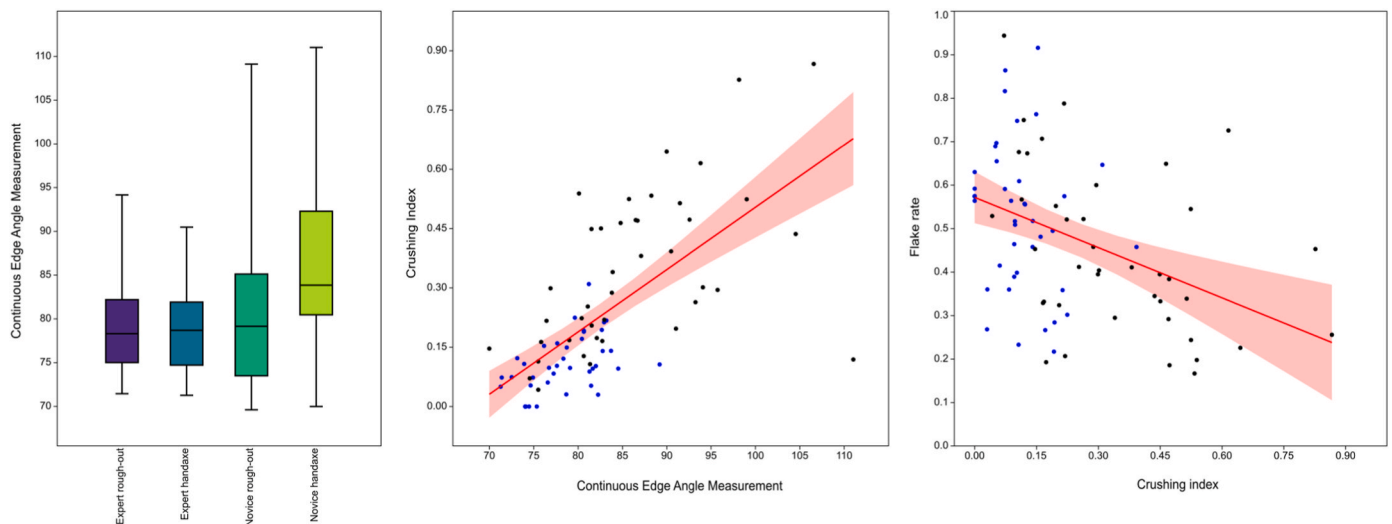


Fig. 5. (A) Boxplots showing medians, interquartile zones and full ranges of CEAM measurements for expert rough-outs (ER), expert handaxes (EH), novice rough-outs (NR) and novice handaxes (NH). (B) Linear regression showing a positive relationship between CEAM and crushing index, from expert (blue) and novice (black) Handaxes. (C) Linear regression showing a significant negative relationship between crushing index and flake rate for expert (blue) and novice (black) handaxes; relationship is insignificant for expert sample. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

threshold is likely to vary substantially by blank attributes, individual knapping style and how the tool is applied to cut and/or modify a worked material, but it is suggested that the rough-out forms produced by novice participants within this study are typically closer to a functional ‘optimum’ than their final configurations (Fig. 6).

4.3. Risk and reward in skill acquisition

Prior knapping studies have tended to contextualise less skilled knappers within a framework of apprenticeship, focusing on their projected journey to expert craftpersons. While this is logical within a modern experimental context, more attention is required for the short-term implications of skill on tool production, with most ‘novice’ knappers in prehistoric contexts presumably intending, or even required, to yield useable products. While reduction schemes followed by expert knappers may be effective when successfully implemented – and aspirational to learners – there has been minimal discussion of associated risks and costs in developing such skills. Over a decade of deliberate practice can be necessary for mastery among adze (biface) makers from Iran Jaya, Indonesia, with apprenticeship traditionally starting during early adolescence; novices visited by Stout (2002) from Langda were not granted access to the best blanks (large flakes) due to failure costs, instead encouraged to produce adzes from subpar materials, often yielding tools too small for use.

The current study evidences a conflict of interests between immediate tool use and long-term skill development; while prolonged flaking sequences improve form regularity, this is associated with an accumulation of errors at the cutting edge. Additional costs and risks for novices include the increased time and energetic expenditure implicit in longer flaking sequences (Pargeter et al., 2024), and the pervasive risk of injury (Gala et al., 2023). Such factors arguably discourage high-fidelity imposition of form at this learning stage, particularly of elements which are functionally neutral, such as Crompton and Gowlett’s (1993) ‘zone of free play’ now evidenced for symmetry and plan-view shape (Machin et al., 2007; Lycett et al., 2016; Key and Lycett, 2017). This supports the importance of imitation (process-based copying) over simple emulation (product-based copying) in early stone tool technologies (Schillinger et al., 2015), showing both the sensitivity of reduction techniques to failure as well as the dangers in observing a model too closely. With limitations to flaking intensity and the extent to which

novices can reconfigure blanks, there is greater motive for less skilled knappers to select materials that are already close to desired forms and to focus flaking on functional portions, such as the working edge. Apparent limitations to novice handaxe reduction also holds implications to tool use-lives (McPherron, 1999; Shimelmitz et al., 2017), with resharping appearing less viable, encouraging tool expedience and reduced mobility.

While risk-aversion may have immediate rewards in functionality, this has implications to long-term skill acquisition. Risk-taking may increase initial utility-related costs, but will expand an individual’s repertoire of known knapping scenarios and cause-effect relationships. Modern knapping experts may present a misleading model for Palaeolithic craftpersons, with few being true toolmakers intending to yield functioning objects. In this context, where goals are often aesthetically based, time constraints are low, and material access is simple, knappers are likely to be high risk-takers, operating comfortably at their zone of proximal development (Vygotsky, 1978). This presumably accelerates learning compared to skill acquisition by active tool users, where pragmatic compromises may be warranted.

Studies of tool use in *Pan* – often used as a conservative model for early hominins (Bandini et al., 2022) – indicate a reluctance to change strategies once one method has been mastered. In a puzzle box study by Marshall-Pescini and Whiten (2008), chimpanzees who had mastered a dipping technique were unreceptive to a slightly more complex (but more productive) method of accessing food from a puzzle box via ‘probing’, despite >200 demonstrations and supplementary tests confirming the strategy was within their capacities. Hrubesch et al. (2009) similarly observed chimpanzees committing to a favoured puzzle box strategy over more lucrative strategies that individuals were also aware of. Observations of wild and captive chimpanzees indicate that young adults are less risk-averse and more proactive in attempting new methods of food provisioning (Matsuzawa, 1996; Haux et al., 2023).

4.4. Acheulean toolmaking

There are clear limitations in comparing lithic products by modern humans to archaeological assemblages produced by early hominins; particularly with participants who only have hours of knapping experience to refer to (Pargeter et al., 2019). While it is assumed that fixed rules of fracture mechanics confine knapping solutions and create some

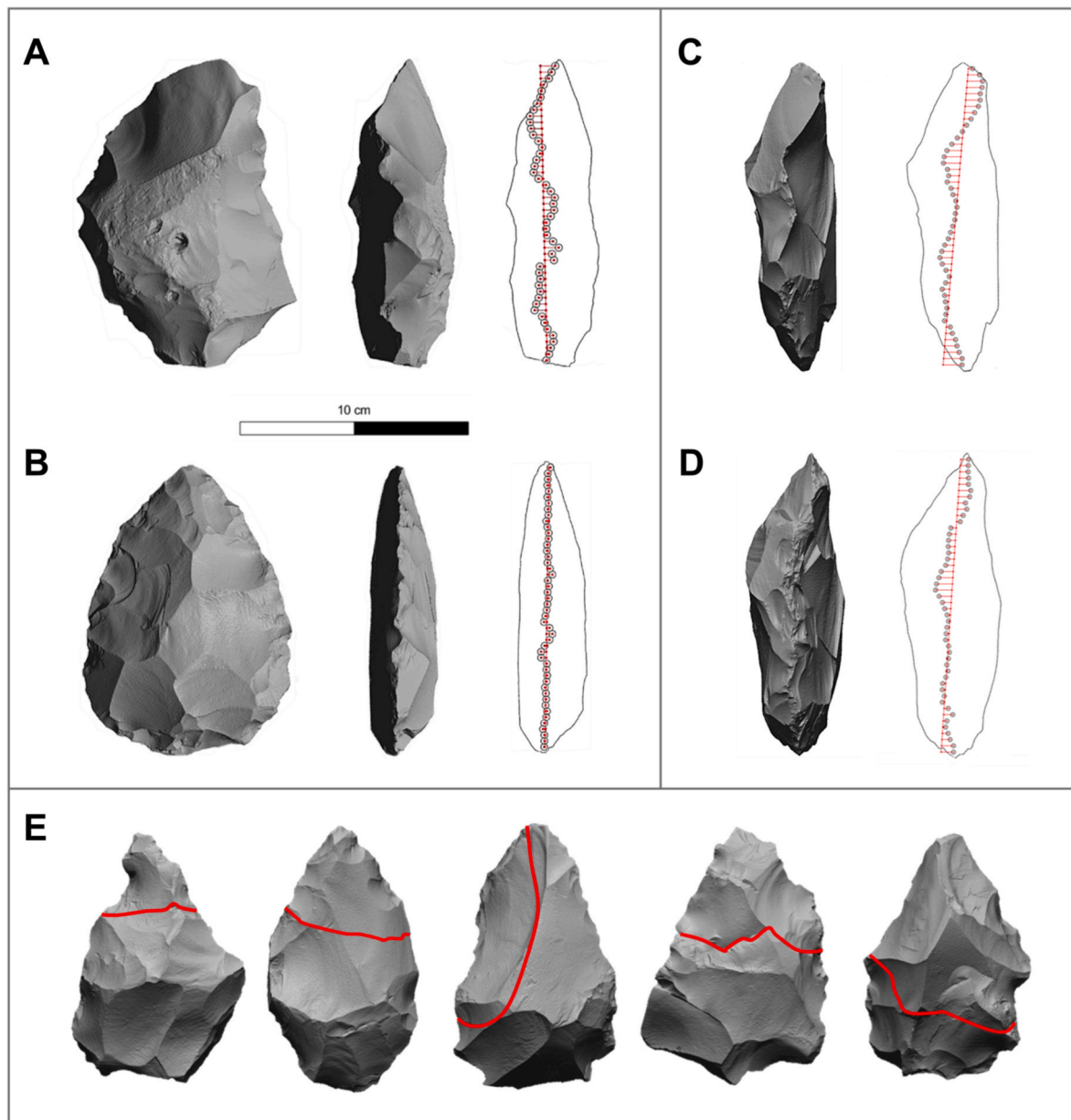


Fig. 6. (A) a novice rough-out with a sinuosity score closest to the mean from this group and stage (186). (B) Finished expert handaxe closest to model form (sinuosity = 40). (C) Novice rough-out prior to extensive edge crushing in the finishing stage (D). (E) Handaxes broken (red lines) by novices in the final stage of shaping. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

common structure in skill progression (Tsirk, 2014), there are significant physiological (Key & Lycett, 2019) and cognitive (Stout et al., 2002) variables that cannot be controlled for when examining Palaeolithic artefacts. These caveats are preferable to just-so theory; provided the hypotheses being tested are clear, as well as the inherent limitations (Eren et al., 2016; Lin et al., 2018; Eren and Meltzer, 2024).

One notable study limitation is the knapping material, with flint predominating northern European lithic technologies but being scarce or absent in other regions. Eren et al. (2014) demonstrated that diverse raw materials (flint, basalt, obsidian) with different fracture properties can be shaped by an expert to near-identical handaxe forms; but variable flaking qualities may be more impactful for less experienced knappers. It is suggested that coarse-grained rocks (e.g., quartzites) have a particular (often limiting) influence on bifacial shaping, ultimately affecting flaking strategies (Wilson et al., 2024). Thus, the appropriacy of archaeological comparisons differs by context; the use of fine-grained flint (and pre-selected flake blanks) is considered a favourable

scenario for novices.

Similarities between modern novice-made handaxes and early Acheulean tools may indicate similar limits in technical knowledge, even if the contexts of manufacture are vastly different. By extension of this argument, less skilled Acheulean hominins likely had similar issues with cumulative edge degradation, encouraging conservative flaking strategies. Comparative handaxe metrics (AGMT3D) from the early Acheulean site of 'Ubeidiya (Layer I-15) (Herzlinger et al., 2021b), indicate similar configurations to the rough-outs produced by novices (bilateral asymmetry = 11.1; bifacial asymmetry = 9.2; edge sinuosity = 172). Herzlinger et al. (2021b) report a positive correlation between biface Scar Density Index (SDI) – used to proxy handaxe reduction intensity (Shipton and Clarkson, 2015) – and bilateral symmetry, and a negative correlation between SDI and refinement, which may represent difficulties in controlling mid-portion volume akin to modern novices. Careful selection of handaxe blanks inferred from early Acheulean assemblages – including the emergence of predetermination in large flake

blanks (Leader et al., 2018; Gossa and Hovers, 2024) – arguably negated prolonged façonnage shaping and error accumulations (Wilson et al., 2024). The prevalence of cortical butts on early Acheulean handaxes (Moncel et al., 2019; Herzlinger et al., 2021b; Ollé et al., 2023) could reflect a reluctance to knap prehensile portions where further reduction and risk is unnecessary.

An important difference between the novice sample and early Acheulean handaxe assemblages is that the latter presumably includes tools made by hominins with years of practice. This presents the question: why did early Pleistocene hominins rarely exceed simple biface strategies? One possible explanation is that handaxes did not require further shaping to support tool functions, with Key (2015) finding no strong advantage to more refined handaxes in set tasks (up to a limit). However, the prevalence of extensively worked handaxe forms across the Middle Pleistocene signifies some advantage to individuals in these contexts, whether practical or social, and relationships between tool-thickness and the ability to impose preferential edge forms in other stone tool types suggests greater refinement could be imposed as a byproduct of attending to alternative attributes (Andrews et al., 2015; Lin and Marreiros, 2021). Regardless of how beneficial thinner and more regularised forms were to hominins, the current study corroborates previous conclusions that there are substantial obstacles to acquiring the supporting skills. Obstacles are not only in time commitment but also in resources, with evidence that practicing longer reduction schemes can conflict immediate goals of toolmaking, creating risks that appear net-negative in early learning. How this risk-reward dynamic changes throughout learning trajectories is unclear, but the plateau in handaxe technology detailed by Parfeter et al. (2019) indicates that the results of this study are not isolated or epiphenomenal of short training periods.

If learning systems in early hominin groups were more like *Pan* than *H. sapiens*, conservative approaches to technology would be anticipated, with implications to long-term skill acquisition and technological ceilings. In such a model, it is possible that the plateau in biface manufacture evidenced in modern humans presented a catchment to knapping skill for Early Pleistocene hominins, with simple biface forms becoming stabilised technological expressions through adulthood. Ecological niche and life history factors may have further played into skill ceilings, if bifaces were sporadically (seasonally) used (Clark and Linares-Matás, 2025); if group sizes were smaller (Mithen, 1994; Lehmann and Wakano, 2013); or lifespans shorter (effecting frequency of older experts) (Kaplan et al., 2000). Childhood and ontogeny is also important in modelling skill acquisition, with this period of cognitive plasticity, play and guardian support providing the most fertile setting for exploratory learning with low failure costs (Nowell, 2016). At a more general level, ecological stability will benefit learning, assuming less pressure on time and resources will buffer costs associated with risk-taking.

Cognition is another highly cited explanation for changes in later Acheulean technology. This has mostly been explored in relation to working memory (Wynn, 1991; Read, 2008; Stout et al., 2014, 2015; Coolidge et al., 2021) but is also important in understanding emotional responses to short-term failure. Managing frustration and accepting short-term costs for long-term gains – as when practicing a skill which is initially counterproductive – can be described as ‘grit’ and is central to models of expertise in other disciplines including sports and music theory (Duckworth et al., 2007). At some level, grit requires self-projection, or Mental Time Travel (MTT), to a future state having mastered the skill with payoff (Suddendorf et al., 2009). Some form of MTT has been indicated in other genera (Zentall, 2006), but it is perceived as being of a different order in humans, complimenting broader hypotheses for Theory of Mind and language acquisition (Suddendorf et al., 2009; Corballis, 2013). While other primates show some propensity for delayed gratification over food resources (Beran, 2021), it is believed that humans uniquely invest in their skills through deliberate practice (Ericsson et al., 1993; Suddendorf et al., 2016).

Passion is highlighted as a key element of grit in modern experts (Duckworth et al., 2007; Bonneville-Roussy et al., 2011; Sigmundsson

and Elmes, 2024) with enjoyment of the learning process motivating practice and mastery. This notion can be tied to existing theories of Acheulean aesthetics, including White and Foulds’ (2018) proposal that superfluous handaxe features including symmetry were driven by dopamine reward systems. This is one evolutionary explanation for aesthetics in material culture, with intrinsic enjoyment of making and learning driving the consolidation of complex technical skills. The occurrence of highly symmetrical LCTs in the archaeological record may signify deep roots to such behaviours (Wynn, 1991; Díez-Martín et al., 2019), even if they were less clearly expressed; perhaps due to practical considerations in bifacial reduction.

5. Conclusions

The current experiment evidences incentives for novices to cease handaxe reduction soon after the establishment of a sharp bifacial edge, sacrificing a level of tool refinement that is theoretically possible but requires risky, net-negative knapping actions during early stages of learning. Similar obstacles are suggested for handaxe manufacture in Acheulean contexts, and the resemblance of many Early Pleistocene handaxe assemblages to novice-made forms may indicate conservative flaking strategies negating the accumulation of edge errors. This interpretation undermines the commonplace characterisation of early Acheulean technology as ‘crude’; a term invoking poor application of a technological concept. In some contexts, the production of simple biface forms is functionally pragmatic, avoiding risks with insubstantial rewards; the judgement of when to stop reduction itself an exercise of expertise, weighing up potentials gains and losses from prior results. Early Pleistocene technology may not be limited by a ceiling in the creative capacity of hominin individuals, but exogenous factors in ecology or social structure, making alternative production modes nonadaptive. While it is unclear what combination of ecological and physiological changes contribute to the expression of advanced shaping strategies in Middle Pleistocene handaxe technology, this change indicates a greater readiness to incur short-term costs of skill acquisition, accelerating repertoire expansion. Plausible factors include greater security in time and resources; prolonged play and practice in childhood/adolescence; social scaffolding by experts; or cognitive propensity for grit and skill investment.

CRedit authorship contribution statement

Finn Stileman: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alastair Key:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Data availability statement

Supporting data is available from an online repository (<https://doi.org/10.17632/3bpz84nj6z.1>) and in the supplementary materials.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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References

- Akhilesh, K., Joshi, P., Bhattacharya, S., Rajagopalan, Y., Baisla, S., Dey, A., Ghaskadbi, S., Karthick, B., Mane, M., Pandey, A., Perur, S., Roy, C., Sharma, A., Sharon, A., Thakar, C., Verma, S., Kashikar, A.S., 2024. Flakes, Feelings, and Finesse: Experimental Studies of Skill Acquisition in Novice Knappers.
- Andrews, B.N., Knell, E.J., Eren, M.I., 2015. The three lives of a uniface. *J. Archaeol. Sci.* 54, 228–236. <https://doi.org/10.1016/j.jas.2014.11.034>.
- Antoine, P., Moncel, M.-H., Limondin-Lozouet, N., Loch, J.-L., Bahain, J.-J., Moreno, D., Voinchet, P., Auguste, P., Stoezel, E., Dabkowski, J., Bello, S.M., Parfitt, S.A., Tombret, O., Hardy, B., 2016. Palaeoenvironment and dating of the early Acheulean localities from the Somme River basin (Northern France): new discoveries from the High terrace at abbeville-carrière carpentier. *Quat. Sci. Rev.* 149, 338–371. <https://doi.org/10.1016/j.quascirev.2016.07.035>.
- Ashton, N., 2015. Ecological niches, technological developments and physical adaptations of early humans in Europe: the handaxe-heidelbergensis hypothesis. In: Coward, F., Wenban-Smith, F., Pope, M., Hosfield, R. (Eds.), *Settlement, Society and Cognition in Human Evolution: Landscapes in Mind*. Cambridge University Press, pp. 138–153. <https://doi.org/10.1017/CBO9781139208697.009>.
- Ashton, N., Davis, R., 2021. Cultural mosaics, social structure, and identity: the Acheulean threshold in Europe. *J. Hum. Evol.* 156, 103011. <https://doi.org/10.1016/j.jhevol.2021.103011>.
- Bandini, E., Harrison, R.A., Motes-Rodrigo, A., 2022. Examining the suitability of extant Primates as models of hominin stone tool culture. *Humanit. Soc. Sci. Commun.* 9 (1). <https://doi.org/10.1057/s41599-022-01091-x>. Article 1.
- Bello, S.M., Delbarre, G., De Groote, I., Parfitt, S.A., 2016. A newly discovered antler flint-knapping hammer and the question of their rarity in the Palaeolithic archaeological record: reality or bias? *Quat. Int.* 403, 107–117. <https://doi.org/10.1016/j.quaint.2015.11.094>.
- Beran, M.J., 2021. Worth the wait: evidence for self-control in nonhuman Primates. In: Anderson, J.R., Kuroshima, H. (Eds.), *Comparative Cognition: Commonalities and Diversity*. Springer, pp. 269–284. https://doi.org/10.1007/978-981-16-2028-7_16.
- Bonneville-Roussy, A., Lavigne, G.L., Vallerand, R.J., 2011. When passion leads to excellence: the case of musicians. *Psychol. Music* 39 (1), 123–138. <https://doi.org/10.1177/0305735609352441>.
- Bril, B., Rein, R., Nonaka, T., Wenban-Smith, F., Dietrich, G., 2010. The role of expertise in tool use: skill differences in functional action adaptations to task constraints. *J. Exp. Psychol. Hum. Percept. Perform.* 36 (4). <https://doi.org/10.1037/a0018171>. Article 4.
- Callahan, E., 1979. The basics of biface knapping in the eastern fluted point tradition: a manual for flintknappers and lithic analysts. *Archaeol. E. N. Am.* 7 (1). Article 1.
- Caruana, M.V., 2020. South African handaxes reloaded. *J. Archaeol. Sci.: Report* 34, 102649. <https://doi.org/10.1016/j.jasrep.2020.102649>.
- Caruana, M.V., 2021. Pilot study comparing the effects of thinning processes on the cross-sectional morphologies of early and late acheulean handaxes. *Archaeometry* 63 (3). <https://doi.org/10.1111/arc.12635>. Article 3.
- Clark, J., Linares-Matás, G.J., 2025. Setbacks in the use of a handaxe: lithic investment and seasonality in the early acheulean. *Archaeol. Anthropol. Sci.* 17 (2), 43. <https://doi.org/10.1007/s12520-024-02133-y>.
- Clark, J., Shipton, C., Moncel, M.-H., Nigst, P., Foley, R., 2024. When is a handaxe a planned-axe? Exploring morphological variability in the Acheulean | PLOS ONE. *PLoS One* 19 (7), e0307081.
- Coolidge, F.L., Wynn, T., Overmann, K.A., 2021. The Evolution of Working Memory. *OSF*. <https://doi.org/10.31235/osf.io/7afp4>.
- Corballis, M.C., 2013. Wandering tales: evolutionary origins of mental time travel and language. *Front. Psychol.* 4. <https://doi.org/10.3389/fpsyg.2013.00485>.
- Crompton, R.H., Gowlett, J.A.J., 1993. Allometry and multidimensional form in Acheulean bifaces from Kilombe, Kenya. *J. Hum. Evol.* 25 (3). <https://doi.org/10.1006/jhevol.1993.1043>. Article 3.
- Davis, R., Ashton, N., Hatch, M., Hoare, P.G., Lewis, S.G., 2021. Palaeolithic archaeology of the Bytham River: human occupation of Britain during the early middle Pleistocene and its European context. *J. Quat. Sci.* 36 (4). <https://doi.org/10.1002/jqs.3305>. Article 4.
- Diez-Martín, F., Wynn, T., Sánchez-Yustos, P., Duque, J., Fraile, C., de Francisco, S., Uribealrrea, D., Mabulla, A., Baquedano, E., Domínguez-Rodrigo, M., 2019. A faltering origin for the acheulean? Technological and cognitive implications from FLK west (Olduvai Gorge, Tanzania). *Quat. Int.* 526, 49–66. <https://doi.org/10.1016/j.quaint.2019.09.023>.
- Duckworth, A.L., Peterson, C., Matthews, M.D., Kelly, D.R., 2007. Grit: perseverance and passion for long-term goals. *J. Pers. Soc. Psychol.* 92 (6), 1087–1101. <https://doi.org/10.1037/0022-3514.92.6.1087>.
- Eren, M.I., Lycett, S.J., Patten, R.J., Buchanan, B., Pargeter, J., O'Brien, M.J., 2016. Test, model, and method validation: the role of experimental stone artifact replication in hypothesis-driven archaeology. *Ethnoarchaeology* 8 (2). <https://doi.org/10.1080/19442890.2016.1213972>. Article 2.
- Eren, M.I., Meltzer, D.J., 2024. Controls, conceits, and aiming for robust inferences in experimental archaeology. *J. Archaeol. Sci.: Report* 53, 104411. <https://doi.org/10.1016/j.jasrep.2024.104411>.
- Eren, M.I., Roos, C.I., Story, B.A., von Cramon-Taubadel, N., Lycett, S.J., 2014. The role of raw material differences in stone tool shape variation: an experimental assessment. *J. Archaeol. Sci.* 49, 472–487. <https://doi.org/10.1016/j.jas.2014.05.034>.
- Ericsson, K.A., Krampe, R.T., Tesch-Romer, C., 1993. The role of deliberate practice in the acquisition of expert performance. *Psychological Review* 100 (3), 363–406.
- Gala, N., Lycett, S.J., Bebbler, M.R., Eren, M.I., 2023. The injury costs of knapping. *Am. Antiq.* 88 (3), 283–301. <https://doi.org/10.1017/aaq.2023.27>.
- Gallotti, R., & Mussi, M. (n.d.). Two Acheuleans, Two Humankinds: from 1.5 to 0.85 Ma at Melka Kunture (Upper Awash, Ethiopian Highlands).
- García-Medrano, P., Despriée, J., Moncel, M.-H., 2022a. Innovations in Acheulean biface production at la Noira (France) during Middle Pleistocene in Western Europe. *Archaeol. Anthropol. Sci.* 14 (4). <https://doi.org/10.1007/s12520-022-01506-5>. Article 4.
- García-Medrano, P., Moncel, M.-H., Maldonado-Garrido, E., Ollé, A., Ashton, N., 2023. The Western European Acheulean: reading variability at a regional scale. *J. Hum. Evol.* 179, 103357. <https://doi.org/10.1016/j.jhevol.2023.103357>.
- García-Medrano, P., Shipton, C., White, M., Ashton, N., 2022b. Acheulean diversity in Britain (MIS 15–MIS11): from the standardization to the regionalization of technology. *Front. Earth Sci.* 10. <https://www.frontiersin.org/articles/10.3389/feart.2022.917207>.
- Gaucherel, C., 2020. Platforms of Palaeolithic Knappers Reveal Complex Linguistic Abilities. *OSF*. <https://doi.org/10.31233/osf.io/wn5za>.
- Geribàs, N., Mosquera, M., Vergès, J.M., 2010. What novice knappers have to learn to become expert stone toolmakers. *J. Archaeol. Sci.* 37 (11). <https://doi.org/10.1016/j.jas.2010.06.026>. Article 11.
- Gossa, T., Hovers, E., 2024. The emergence of large flake-based Acheulian technology: perspective from the highland site-complex of Melka Wakena, Ethiopia. *Archaeol. Anthropol. Sci.* 16 (10), 172. <https://doi.org/10.1007/s12520-024-02072-8>.
- Gowlett, J., 2006. The elements of design form in Acheulian bifaces: Modes, modalities, rules and language. In: *Axe Age: Acheulian Toolmaking from Quarry to Discard*. Equinox, pp. 203–222.
- Gowlett, J., 2015. Variability in an early hominin percussive tradition: the Acheulean versus cultural variation in modern chimpanzee artefacts. *Phil. Trans. Biol. Sci.* 370 (1682), 20140358. <https://doi.org/10.1098/rstb.2014.0358>.
- Haux, L.M., Engelmann, J.M., Arslan, R.C., Hertwig, R., Herrmann, E., 2023. Chimpanzee and human risk preferences show key similarities. *Psychol. Sci.* 34 (3), 358–369. <https://doi.org/10.1177/09567976221140326>.
- Herzlinger, G., Brenet, M., Varanda, A., Deschamps, M., Goren-Inbar, N., 2021b. Revisiting the acheulian large cutting tools of 'Ubeidiya, Israel. *Journal of Paleolithic Archaeology* 4 (4). <https://doi.org/10.1007/s41982-021-00108-2>. Article 4.
- Herzlinger, G., Grosman, L., 2018. AGMT3-D: a software for 3-D landmarks-based geometric morphometric shape analysis of archaeological artifacts. *PLoS One* 13 (11). <https://doi.org/10.1371/journal.pone.0207890>. Article 11.
- Herzlinger, G., Varanda, A., Deschamps, M., Brenet, M., Lopez-Tascon, C., Goren-Inbar, N., 2021a. Reevaluation of the classification scheme of the acheulian in the levant - 50 years later: a morpho-technological analysis of handaxe variability. *PaleoAnthropology*. <https://doi.org/10.48738/2021.iss1.70>.
- Hicks, J., 2023. A volumetric analysis of handaxe symmetry referencing a known symmetrical ideal. <https://doi.org/10.21203/rs.3.rs-2551323/v1>.
- Hubesch, C., Preuschoft, S., van Schaik, C., 2009. Skill mastery inhibits adoption of observed alternative solutions among chimpanzees (Pan troglodytes). *Anim. Cognit.* 12 (2), 209–216. <https://doi.org/10.1007/s10071-008-0183-y>.
- Hutchence, L., Debackere, S., 2019. An evaluation of behaviours considered indicative of skill in handaxe manufacture. *Lithics: The Journal of the Lithic Studies Society*. <https://www.semanticscholar.org/paper/An-evaluation-of-behaviours-considered-indicative-Hutchence-Debackere/505fe1a14ec45b65897f7964e94002ab8712a364>.
- Isaac, G.L., 1977. *Ologesailie: Archaeological Studies of a Middle Pleistocene Lake Basin in Kenya*. University of Chicago Press.
- Jagher, R., Elsuede, H., Le Tensorer, J.-M., 2015. El Kowm Oasis, human settlement in the Syrian Desert during the Pleistocene. *L'Anthropologie* 119 (5). <https://doi.org/10.1016/j.anthro.2015.10.003>. Article 5.
- Kaplan, H., Hill, K., Lancaster, J., Hurtado, A.M., 2000. A theory of human life history evolution: Diet, intelligence, and longevity. *Evol. Anthropol. Issues News Rev.* 9 (4), 156–185. [https://doi.org/10.1002/1520-6505\(2000\)9:4<156::AID-EVAN5>3.0.CO;2-7](https://doi.org/10.1002/1520-6505(2000)9:4<156::AID-EVAN5>3.0.CO;2-7).
- Key, A., 2022. The Acheulean is a temporally cohesive tradition. *World Archaeol.* 54 (3). <https://doi.org/10.1080/00438243.2023.2169340>. Article 3.

- Key, A., 2024. Regional extinction(s) but continental persistence in European Acheulean culture. *Cambridge Prisms: Extinction* 1–29. <https://doi.org/10.1017/ext.2024.13>.
- Key, A.J.M., 2015. *Form and Function in the Lower Palaeolithic*. University of Kent.
- Key, A.J.M., 2019. Handaxe shape variation in a relative context. *C. R. Palevol* 18 (5). <https://doi.org/10.1016/j.crpv.2019.04.008>. Article 5.
- Key, A.J.M., Lycett, S.J., 2017. Influence of handaxe size and shape on cutting efficiency: a large-scale experiment and morphometric analysis. *J. Archaeol. Method Theor* 24 (2). <https://doi.org/10.1007/s10816-016-9276-0>. Article 2.
- Kuhn, S.L., 2021. *The Evolution of Paleolithic Technologies*. Routledge. <https://doi.org/10.4324/9781315642024>.
- Leader, G.M., Kuman, K., Gibbon, R.J., Granger, D.E., 2018. Early Acheulean organised core knapping strategies ca. 1.3 Ma at Rietputs 15, Northern Cape Province, South Africa. *Quat. Int.* 480, 16–28. <https://doi.org/10.1016/j.quaint.2016.08.046>.
- Lehmann, L., Wakano, J.Y., 2013. The handaxe and the microscope: individual and social learning in a multidimensional model of adaptation. *Evol. Hum. Behav.* 34 (2), 109–117. <https://doi.org/10.1016/j.evolhumbehav.2012.11.001>.
- Lin, S.C., Marreiros, J., 2021. Quina Retouch does not maintain edge angle over reduction. *Lithic Technol.* 46 (1). <https://doi.org/10.1080/01972761.2020.1819048>. Article 1.
- Lin, S.C., Rezek, Z., Dibble, H.L., 2018. Experimental design and experimental inference in stone artifact archaeology. *J. Archaeol. Method Theor* 25 (3). <https://doi.org/10.1007/s10816-017-9351-1>. Article 3.
- Liu, C., Khreisheh, N., Stout, D., Pargeter, J., 2023. Differential effects of knapping skill acquisition on the cultural reproduction of late acheulean handaxe morphology: archaeological and experimental insights. *J. Archaeol. Sci.: Report* 49, 103974. <https://doi.org/10.1016/j.jasrep.2023.103974>.
- Lycett, S.J., 2009. Understanding Ancient hominid dispersals using artefactual data: a phylogeographic analysis of Acheulean handaxes. *PLoS One* 4 (10). <https://doi.org/10.1371/journal.pone.0007404>. Article 10.
- Lycett, S.J., Eren, M.I., 2019. Built-in misdirection: on the difficulties of learning to knap. *Lithic Technol.* 44 (1). <https://doi.org/10.1080/01972761.2018.1539322>. Article 1.
- Lycett, S.J., Gowlett, J.A.J., 2008. On questions surrounding the acheulean 'tradition'. *World Archaeol.* 40 (3). <https://doi.org/10.1080/00438240802260970>. Article 3.
- Lycett, S.J., Schillinger, K., Eren, M.I., von Cramon-Taubadel, N., Mesoudi, A., 2016. Factors affecting Acheulean handaxe variation: experimental insights, microevolutionary processes, and macroevolutionary outcomes. *Quat. Int.* 411, 386–401. <https://doi.org/10.1016/j.quaint.2015.08.021>.
- Machin, A.J., Hosfield, R.T., Mithen, S.J., 2007. Why are some handaxes symmetrical? Testing the influence of handaxe morphology on butchery effectiveness. *J. Archaeol. Sci.* 34 (6). <https://doi.org/10.1016/j.jas.2006.09.008>. Article 6.
- Marshall-Pescini, S., Whiten, A., 2008. Chimpanzees (*Pan troglodytes*) and the question of cumulative culture: an experimental approach. *Anim. Cognit.* 11 (3), 449–456. <https://doi.org/10.1007/s10071-007-0135-y>.
- Matsuzawa, T., 1996. Chimpanzee intelligence in nature and in captivity: isomorphism of symbol use and tool use. In: Marchant, L.F., Nishida, T., McGrew, W.C. (Eds.), *Great Ape Societies*. Cambridge University Press, pp. 196–210. <https://doi.org/10.1017/CBO9780511752414.017>.
- McPherron, S.P., 1999. *Ovate and pointed handaxe assemblages: two points make a line*. *Préhistoire Européenne* 14, 9–32.
- Mithen, S., 1994. Technology and Society during the Middle Pleistocene: Hominid Group size, social learning and industrial variability. *Cambridge Archaeol. J.* 4 (1). <https://doi.org/10.1017/S0959774300000949>. Article 1.
- Moigne, A.-M., Valensi, P., Auguste, P., García-Solano, J., Tuffreau, A., Lamotte, A., Barroso, C., Moncel, M.-H., 2016. Bone retouchers from Lower Palaeolithic sites: Terra Amata, Orgnac 3, Cagny-l'Épinette and Cueva del Angel. *Quat. Int.* 409, 195–212. <https://doi.org/10.1016/j.quaint.2015.06.059>.
- Moncel, M.-H., Ashton, N., Lamotte, A., Tuffreau, A., Cluquet, D., Despriée, J., 2015. The early acheulean of north-western Europe. *J. Anthropol. Archaeol.* 40, 302–331. <https://doi.org/10.1016/j.jaa.2015.09.005>.
- Moncel, M.-H., Despriée, J., Voinchet, P., Courcmault, G., Hardy, B., Bahain, J.-J., Puaud, S., Gallet, X., Falguères, C., 2016. The Acheulean workshop of la Noira (France, 700 ka) in the European technological context. *Quat. Int.* 393, 112–136. <https://doi.org/10.1016/j.quaint.2015.04.051>.
- Moncel, M.-H., Santagata, C., Pereira, A., Nomade, S., Bahain, J.-J., Voinchet, P., Piperno, M., 2019. A biface production older than 600 ka ago at Notarchirico (Southern Italy) contribution to understanding early Acheulean cognition and skills in Europe. *PLoS One* 14 (9). <https://doi.org/10.1371/journal.pone.0218591>. Article 9.
- Mosquera, M., Ollé, A., Rodríguez, X.P., 2013. From Atapuerca to Europe: tracing the earliest peopling of Europe. *Quat. Int.* 295, 130–137. <https://doi.org/10.1016/j.quaint.2012.01.031>.
- Muller, A., Sharon, G., Grosman, L., 2025. The skills of handaxe making: quantifying and explaining variability in 3D sinuosity and bifacial asymmetry. *J. Archaeol. Method Theor* 32 (2), 35. <https://doi.org/10.1007/s10816-025-09705-9>.
- Mussi, M., Altamura, F., Di Bianco, L., Bonnefille, R., Gaudzinski-Windheuser, S., Geraads, D., Melis, R.T., Panera, J., Piarulli, F., Pioli, L., Ruta, G., Sánchez-Dehesa Galán, S., Méndez-Quintas, E., 2023. After the emergence of the Acheulean at Melka Kunture (Upper Awash, Ethiopia): from Gombore IB (1.6 Ma) to Gombore Iy (1.4 Ma), Gombore Iδ (1.3 Ma) and Gombore II OAM Test Pit C (1.2 Ma). *Quat. Int.* 657, 3–25. <https://doi.org/10.1016/j.quaint.2021.02.031>.
- Mussi, M., Gallotti, R., 2017. Two Acheuleans, two humankinds: from 1.5 to 0.85 Ma at Melka Kunture (Upper Awash, Ethiopian highlands). *J. Archaeol. Sci.* 95, 1–46.
- Newcomer, M.H., 1971. Some quantitative experiments in handaxe manufacture. *World Archaeol.* 3 (1). <https://doi.org/10.1080/00438243.1971.9979493>. Article 1.
- Nonaka, T., Bril, B., Rein, R., 2010. How do stone knappers predict and control the outcome of flaking? Implications for understanding early stone tool technology. *J. Hum. Evol.* 59 (2). <https://doi.org/10.1016/j.jhevol.2010.04.006>. Article 2.
- Nowell, A., 2016. Childhood, play and the evolution of cultural capacity in neanderthals and modern humans. In: *Vertebrate Paleobiology and Paleoanthropology*, pp. 87–97. https://doi.org/10.1007/978-94-017-7426-0_9.
- Ollé, A., Lombao, D., Asryan, L., García-Medrano, P., Arroyo, A., Fernández-Marchena, J. L., Yeşilova, G.C., Cáceres, I., Huguet, R., López-Polín, L., Pineda, A., García-Taberner, A., Fidalgo, D., Rosas, A., Saladié, P., Vallverdú, J., 2023. The earliest European Acheulean: new insights into the large shaped tools from the late Early Pleistocene site of Barranc de la Boella (Tarragona, Spain). *Front. Earth Sci.* 11. <https://www.frontiersin.org/articles/10.3389/feart.2023.1188663>.
- Paige, J., Perreault, C., 2024. 3.3 million years of stone tool complexity suggests that cumulative culture began during the Middle Pleistocene. *Proc. Natl. Acad. Sci.* 121 (26), e2319175121. <https://doi.org/10.1073/pnas.2319175121>.
- Pargeter, J., Cebeiro, A., Levy, S.B., 2024. Stone toolmaking energy expenditure differs between novice and expert toolmakers. *American Journal of Biological Anthropology* 185 (4), e25026. <https://doi.org/10.1002/ajpa.25026>.
- Pargeter, J., Khreisheh, N., Stout, D., 2019. Understanding stone tool-making skill acquisition: experimental methods and evolutionary implications. *J. Hum. Evol.* 133, 146–166. <https://doi.org/10.1016/j.jhevol.2019.05.010>.
- Putt, S.S., Woods, A.D., Franciscus, R.G., 2014. The role of verbal interaction during experimental bifacial stone tool manufacture. *Lithic Technol.* 39 (2). <https://doi.org/10.1179/0197276114Z.00000000036>. Article 2.
- Read, D.W., 2008. Working memory: a cognitive limit to non-human primate recursive thinking prior to Hominid evolution. *Evol. Psychol.* 6 (4), 147470490800600413. <https://doi.org/10.1177/147470490800600413>.
- Rein, R., Bril, B., Nonaka, T., 2013. Coordination strategies used in stone knapping. *Am. J. Phys. Anthropol.* 150 (4), 539–550. <https://doi.org/10.1002/ajpa.22224>.
- Sánchez-Dehesa Galán, S., Méndez-Quintas, E., Bahain, J.-J., di Bianco, L., Bonnefille, R., Brunelli, E., Geraads, D., Melis, R., Domínguez, A.S., Voinchet, P., Mussi, M., 2022. Age and formation processes of an Acheulean site with extensive accumulation of large cutting tools: Garba I (Melka Kunture, Upper Awash, Ethiopia). *Archaeol. Anthropol. Sci.* 14 (3), 55. <https://doi.org/10.1007/s12520-022-01521-6>.
- Schick, K., Toth, N., 2017. Acheulean industries of the early and middle Pleistocene, middle awash, Ethiopia. *L'Anthropologie* 121 (5). <https://doi.org/10.1016/j.anthro.2017.10.009>. Article 5.
- Schillinger, K., Mesoudi, A., Lycett, S.J., 2015. The impact of imitative versus emulative learning mechanisms on artifactual variation: implications for the evolution of material culture. *Evol. Hum. Behav.* 36 (6). <https://doi.org/10.1016/j.evolhumbehav.2015.04.003>. Article 6.
- Schreve, D., Moncel, M.-H., Bridgland, D., 2015. Editorial: chronology, palaeoenvironments and subsistence in the Acheulean of western Europe. *J. Quat. Sci.* 30 (7), 585. <https://doi.org/10.1002/jqs.2820>.
- Shelley, P.H., 1990. Variation in lithic assemblages: an experiment. *J. Field Archaeol.* 17 (2), 187–193. <https://doi.org/10.1179/009346990791548349>.
- Shimelmitz, R., Bisson, M., Weinstein-Evron, M., Kuhn, S.L., 2017. Handaxe manufacture and re-sharpening throughout the Lower Palaeolithic sequence of Tabun Cave. *Quat. Int.* 428, 118–131. <https://doi.org/10.1016/j.quaint.2015.12.076>.
- Shipton, C., 2018. Biface knapping skill in the East African acheulean: progressive trends and random walks. *Afr. Archaeol. Rev.* 35 (1). <https://doi.org/10.1007/s10437-018-9287-1>. Article 1.
- Shipton, C., 2019. The evolution of social transmission in the acheulean. In: Overmann, K.A., Coolidge, F.L. (Eds.), *Squeezing Minds from Stones: Cognitive Archaeology and the Evolution of the Human Mind*. Oxford University Press. <https://doi.org/10.1093/oso/9780190854614.003.0017>.
- Shipton, C., Clarkson, C., 2015. Flake scar density and handaxe reduction intensity. *J. Archaeol. Sci.: Report* 2, 169–175. <https://doi.org/10.1016/j.jasrep.2015.01.013>.
- Sigmundsson, H., Elnes, M., 2024. From passion to expertise. In: Sigmundsson, H., Elnes, M. (Eds.), *Understanding Passion: the Key to Success*. Springer, Nature Switzerland, pp. 45–54. https://doi.org/10.1007/978-3-031-66910-1_4.
- Stade, C.M., 2017. *Lithic Morphological Variability as a Proxy for Palaeolithic Linguistic Ability: a Knapping Training Study Exploring Cultural Transmission, Theory of Mind and Language* [Phd. University of Southampton]. <https://eprints.soton.ac.uk/416633/>.
- Stout, D., 2002. Skill and cognition in stone tool production: an ethnographic case study from irian jaya. *Curr. Anthropol.* 43 (5). <https://doi.org/10.1086/342638>. Article 5.
- Stout, D., 2011. Stone toolmaking and the evolution of human culture and cognition. *Phil. Trans. Biol. Sci.* 366 (1567). <https://doi.org/10.1098/rstb.2010.0369>. Article 1567.
- Stout, D., Apel, J., Commander, J., Roberts, M., 2014. Late Acheulean technology and cognition at Boxgrove, UK. *J. Archaeol. Sci.* 41, 576–590. <https://doi.org/10.1016/j.jas.2013.10.001>.
- Stout, D., Hecht, E., Khreisheh, N., Bradley, B., Chaminade, T., 2015. Cognitive demands of lower Paleolithic toolmaking. *PLoS One* 10 (4). <https://doi.org/10.1371/journal.pone.0121804>. Article 4.
- Suddendorf, T., Addis, D.R., Corballis, M.C., 2009. Mental time travel and the shaping of the human mind. *Phil. Trans. Biol. Sci.* 364 (1521), 1317–1324. <https://doi.org/10.1098/rstb.2008.0301>.
- Suddendorf, T., Brinums, M., Imuta, K., 2016. Shaping one's future self: the development of deliberate practice. In: Michaelian, K., Klein, S.B., Szpunar, K.K. (Eds.), *Seeing the Future: Theoretical Perspectives on Future-Oriented Mental Time Travel*. Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780190241537.003.0017>.
- Torres, C., Preysler, J.B., 2020. Experts also fail: a new methodological approach to skills analysis in lithic industries. *Journal of Paleolithic Archaeology* 3 (4). <https://doi.org/10.1007/s41982-020-00063-4>. Article 4.

- Vaughan, D., 2001. A million years of style and function: regional and temporal variation in acheulean handaxes. In: Hurt, T.D., Rakita, G.F.M. (Eds.), *Style and Function: Conceptual Issues in Evolutionary Archaeology*. Bergin & Garvey, pp. 141–163.
- Viallet, C., Grégoire, S., Perrenoud, C., 2022. Break to Rebuild—The First European Evidence of a Fragmented Chaîne Opératoire for Handaxe Production (OIS 14, Caune de l’Arago, France). *Journal of Paleolithic Archaeology* 5 (1). <https://doi.org/10.1007/s41982-022-00116-w>. Article 1.
- Vygotsky, L.S., 1978. *Mind in Society: Development of Higher Psychological Processes*. Harvard University Press. <https://doi.org/10.2307/j.ctvjf9vz4>.
- Wenban-Smith, F.F., 1989. The use of canonical variates for determination of biface manufacturing technology at boxgrove lower palaeolithic site and the behavioural implications of this technology. *J. Archaeol. Sci.* 16 (1). [https://doi.org/10.1016/0305-4403\(89\)90053-8](https://doi.org/10.1016/0305-4403(89)90053-8). Article 1.
- White, M., Foulds, F., 2018. Symmetry is its own reward: on the character and significance of Acheulean handaxe symmetry in the Middle Pleistocene. *Antiquity* 92 (362), 304–319. <https://doi.org/10.15184/aqy.2018.35>.
- Whittaker, J., 1994. *Flintknapping: Making and Understanding Stone Tools: Vol. 1st Ed.* University of Texas Press. https://ezp.lib.cam.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=941097&site=ehost-live&sc_ope=site.
- Williams-Hatala, E.M., Hatala, K.G., Key, A., Dunmore, C.J., Kasper, M., Gordon, M., Kivell, T.L., 2021. Kinetics of stone tool production among novice and expert tool makers. *Am. J. Phys. Anthropol.* 174 (4), 714–727. <https://doi.org/10.1002/ajpa.24159>.
- Wilson, C.G., Caruana, M.V., 2024. Acheulean in Southern Africa: latest perspectives. In: *The International Encyclopedia of Anthropology*. John Wiley & Sons, Ltd, pp. 1–14. <https://doi.org/10.1002/9781118924396.wbiea2548>.
- Wilson, C.G., Caruana, M.V., Blackwood, A.F., Arnold, L.J., Herries, A.I.R., 2024. Why large flakes? Later acheulian handaxe manufacture at Amanzi Springs, Area 2 (Eastern Cape, South Africa). *J. Archaeol. Sci.: Report* 53, 104393. <https://doi.org/10.1016/j.jasrep.2024.104393>.
- Wynn, T., 1991. Tools, grammar and the archaeology of cognition. *Camb. Archaeol. J.* 1 (2). <https://doi.org/10.1017/S0959774300000354>. Article 2.
- Wynn, T., 1995. *Handaxe enigmas*. *World Archaeol.* 27 (1). Article 1.
- Wynn, T., 2002. Archaeology and cognitive evolution. *Behav. Brain Sci.* 25 (3), 389–402. <https://doi.org/10.1017/S0140525X02000079>.
- Zentall, T.R., 2006. Mental time travel in animals: a challenging question. *Behav. Process.* 72 (2), 173–183. <https://doi.org/10.1016/j.beproc.2006.01.009>.