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RESEARCH

The use of shaped stone balls to extract marrow: a matter of skill? Experimental- traceological approach

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Abstract

Technological skills associated with the Paleolithic culture have been explored extensively in recent years, with regard to the production of stone tools. Aspects of skill related to the use of these tools, however, have yet to be comprehensively explored. In this paper, we use a combined experimental-traceological approach to explore aspects of skill in the use of Lower Paleolithic (LP) shaped stone balls (SSBs) as percussion tools for marrow extraction. We examine the effect of skill, or lack thereof, on the accumulation of distinctive use wear traces upon these implements, while also considering handling, grip, and body posture of skilled versus unskilled participants in our experiment. In addition, we investigate possible indicative morphologies attesting to skill level on the processed bones. The results show that the observed differences in body posture, gestures, tool gripping and handling of skilled versus unskilled individuals influenced the intensity and dispersion of wear traces on the tools. Moreover, differences were also detected with regard to the processed bones. Thus, our study shows that while we tend to think that bone-breaking is intuitive, it in fact requires planning, knowledge of bone anatomy and tool use, as well as skill and experience. We hope that these experimental insights will offer a better grounding for understanding human skill and its visible expression on material culture.

Keywords Early humans · Lithic macro tools · Bone breaking · Skill levels

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Introduction

Technological skills associated with the Paleolithic culture have been explored extensively in recent years, mostly with regard to the production of stone tools. Common methods are the application of techno-typological and/or morphometric analysis of archaeological artifacts combined with experimental results (e.g. Finlay 2008; Geribàs et al. 2010; Nichols and Allstadt 1978; Nonaka et al. 2010; Shelley 1990; Sternke and Sørensen 2009; Torres and Preysler 2020; Torres Navas 2022; Winton 2004) and ethnographic observations (e.g. Arthur 2010, 2018; Stout 2005). These studies examine the products of skilled versus unskilled knappers, and demonstrate that the products of less experienced knappers can be distinguished by recognizable differences in form, regularity, and metrics. Thus, aspects of technical skills, or lack thereof, can be reflected in prehistoric assemblages from the Lower Paleolithic (LP) period onwards (*e.g.*, Assaf 2021a, 2021b; Bamforth and Finlay 2008; Herzlinger et al. 2017; Högberg 2008; Langley 2020; Maloney 2019; Pelegrin 1990; Pigeot 1990; Shipton 2010; Takakura and Naoe 2019; Torres and Preysler 2020). But what about aspects of skill associated with the *use* of these stone tools?

Ingold (2001) notes that using a tool involves the hands, eyes, and in fact the entire body. Taking into account the functional relationship between tool and tool-user (Malafouris 2010), we can expect that an unskilled tool user has an "un-skilled body" and unskilled gestures, which in turn affect the functional traces and characteristics of the tool itself. Apprenticeship may lead to a visible expression on the tools and materials processed by them. Thus, when we look at a group of artifacts, variability might derive not only from the skill of the knapper, but also from the competence of the user (Bleed 2008). If so, we can expect to find evidence of different skill levels in the archaeological record.

Traceological analysis, supported by experimental data, could be effective methods for identifying such evidence. However, use-wear analysis supported by experimental studies is usually applied to better understand stone tool function rather than to identify how well the user performed a certain task. One exception is the study of Van Gijn (1990: 26), who reported that tools used by skilled individuals may exhibit different use-wear features than tools used by inexperienced ones for the same task. Moreover, the user's skill should be evident in the use-wear traces regardless of whether the tool was used briefly or at length. These insights were applied to the study of LP stone tools from Qesem Cave (420,000–200,000 ybp), Israel, where specific items—recycled flake products—were shown to bear weak traces of use, which may indicate less-skilled butchers. These items were found in an area used to practice the basics of knapping, indicating that learning in the cave was a holistic process that integrated the production of prehistoric stone tools and their use (Assaf et al. 2023a).

Several studies indicate that cut marks upon bones may shed light on the skill of the butcher (Egeland et al. 2014). The direction of the cut marks and the fracture patterns of bones testify to the learning processes of defleshing, disarticulation, and skinning (Egeland et al. 2014; Willis and Boehm 2015). In Qesem Cave, randomly oriented cut marks were identified on several bones. These marks suggest that several individuals— skilled and unskilled—may have been involved in removing the meat from the bones (Stiner et al. 2009, 2011). Nonetheless, we lack experimental data that could ultimately support the identification of skill level in Paleolithic stone tool assemblages.

In this paper, we use a combined experimental-traceological approach to explore aspects of skill in the use of shaped stone balls as percussion tools for marrow extraction. We examine the effect of skill, or lack thereof, on the accumulation of distinctive use wear traces upon these implements, while also considering handling, grip, and body posture of skilled versus unskilled participants in our experiment. In addition, we investigate possible indicative morphologies attesting to skill level on the processed bones.

Percussive artefacts form a significant component of Paleolithic lithic assemblages and appear alongside other technological trajectories. Scholars have studied early Paleolithic percussive technologies to understand the origins of human cognition and address questions about paleo diet and subsistence (Arroyo and de la Torre, 2020; Bril et al., 2012; Carvalho et al., 2019). Experimental archaeology, functional analyses and techno-morphometric analyses show that these implements were passive and active, used as hammerstones for knapping, for the processing of vegetal materials (see Goren-Inbar et al. 2015), and – very commonly, for bone breaking.

This study focuses the percussive artefacts used to break bones and extract bone marrow – one of the most common activities in the Paleolithic period (Blasco et al. 2013, 2016; Blumenschine 1995; Bunn 1981; Ferraro et al. 2013; Pobiner et al. 2008), related to to the growing need for fat consumption (Ben-Dor et al. 2021; Plummer et al. 2023).

Marrow can be obtained from the bones of mammals using various techniques, such as hitting, crushing and grinding (Outram 2001), or in other words by applying different types of loading to these bones, as defined by Gifford-Gonzalez (2018): *Static* loading (gradual increase in pressure until the bone undergoes structural failure), *Dynamic* loading (sudden impact loads the bone with stress that exceeds the failure point, either with cracks intersecting one another or through catastrophic structural collapse), and *Torsional* loading (twisting beyond the bone's ability to resist stress produces a crack and break).

These different forms of bone processing were observed ethnographically in present-day hunter-gatherers (Blasco et al. 2013; Bonnichsen 1973), and were observed in the archaeological record as well: Dart (1959) and Sadek-Kooros (1972) suggested "crack-and-twist" technique used by australopithecines. Percussion by batting, when the bone is hit directly against a stone object or an anvil was observed by Blasco et al. 2013 in Bolomor cave. In this case, human groups also combined the actions of their hands and teeth in order to fracture the small prey bones. Mostly, however, it seems that humans gained access to marrow by striking the diaphysis usually at right angles to the long axis of the bone in a *dynamic loading*, using a stone or other modified or unmodified percussors (see for example Domínguez-Rodrigo and Barba 2006, Blasco et al. 2013; Blumenschine 1995, Blumenschine et al., 2007, Blumenschine and Selvaggio 1988; Capaldo and Blumenschine 1994; Capaldo 1997).

Here, we focused on one common type of these percussive implements—shaped stone balls (i.e., spheroids and polyhedrons, hereinafter SSBs). Geographically, SSBs appear to have originated in Oldowan and Early Acheulean toolkits in Africa. They are also documented in the Levant and Europe, and in southern and eastern Asia (Barkai and Gopher 2016; Bar-Yosef and Goren-Inbar 1993; Barsky et al. 2015; Bourguignon et al. 2016; Cabanès et al. 2022; Corvinus-Karve 1968; García-Vadillo et al. 2022; Geraads et al. 1986; Isaac and Isaac 1977; Kuman et al. 1997; Leakey 1971; Le Tensorer et al. 2011; Li et al. 2017; Marder et al. 2007; Paddayya 1977; Piperno et al. 2009; Raynal et al. 2004; Robinson and Mason 1962; Sahnouni et al. 2002; Sahnouni et al. 2018; Sharon et al. 2010; Shemer et al. 2019; Willoughby 1985; Yang et al. 2014). SSBs were interpreted in various ways: as bolas or throwing stones for capturing animals (Clark 1982; Isaac 1987; Leakey 1931); as food-pounding tools (Yustos et al. 2015); as exhausted cores (Sahnouni et al. 1997; Schick and Toth 1994); as hammerstones (Jones 1994; Roussel et al. 2011; Willoughby 1985); and as battering tools for processing vegetal material or tendering meat (Mora and de la Torre 2005). They are considered by some as end-products of a preconceived shaping process (Muller et al. 2023; Texier and Roche 1995; Titton et al. 2020; De Weyer 2017), while others interpret them as by-products of specific technological or functional trajectories (Jones 1994; Roussel et al. 2011; Sahnouni et al. 1997). Based on functional- experimental studies, we previously showed that SSBs were used for bone marrow extraction (Assaf et al. 2020, 2023b; Assaf 2024). Residue and use wear traces observed on SSBs from the LP site of Qesem Cave directly associate these items with marrow extraction (Assaf et al. 2020). Contextual analysis shows an association of these items with medium-large sized herbivores in Qesem Cave (Equus *ferus*), and possibly in other African and Levantine sites (Assaf 2024). Experimental studies support this hypothesis, showing that this is in fact a very effective hand-held percussion implement due to its round morphology and unique ergonomic features – the intersecting high ridges (Assaf and Baena 2022). Moreover, despite their differences in size, the modern human palm and SSB vary with the same pattern of proportions and display a similar range of width (Assaf et al. 2023b). It should be noted that these implements may have been used for additional percussive activities, as mentioned above (Cabanès et al. 2024). But since the main purpose of this study is to investigate the skill needed when using percussion instruments to break bones, we chose to focus on this specific activity performed with these items.

We compare the procedure and traces associated with marrow extraction with SSBs in expert and non-expert tool-users, under the null hypothesis of no differences, and the way different skill levels might be reflected on these items in terms of use wear accumulation as well as on the processed material (i.e. animal bones). Finally, this research is a preliminary and descriptive survey, aimed at providing basic information to further develop this issue. We hope that these experimental insights will offer a better grounding for understanding human skill and its visible expression on material culture.

Materials and methods

The study integrates experimental analysis (stage 1) with traceological analysis (stage 2). The experimental protocol includes the manipulation and use of SSB replicas (produced by J.B.P.) for bone breaking and marrow extraction by skilled and unskilled participants. The traceological analysis includes (a) the study of use-wear traces accumulated upon the SSBs during the experiment and (b) taphonomic analysis of the processed materials, i.e. bones, to examine possible morphologies attesting to skill level.

Stage 1 The experiment focused on the comparison of skilled versus unskilled participants while addressing the following questions and parameters: planning, efficiency of marrow extraction (without contamination by bone splinters), body gestures and postures, and the way the tool and the bones were handled and gripped. Six participants took part in the experiment, which was conducted in the Experimental Archaeological Laboratory of UAM: two experienced bone breakers (J.B.P., J. R.) and four unexperienced bone breakers, two men and two women. The skilled participants have years of experience: J. Rosell is a zooarchaeologist who managed and actively participated in multiple experiments involving bone marrow extraction (see Assaf et al. 2020; Blasco et al. 2013, 2014, 2019) and J.B Preysler conducted and participated in experiments involving bone processing as part of the management of the Experimental Archaeology Laboratory at UAM for decades. The unskilled participants are students in the Archaeology Department of UAM who have basic tool knapping skills. The hand palm (length and width) of all participants was measured (Table 1). Nine SSB replicas were used to break limb bones of cows and pigs (Table 2). The replicas (Table 1) were made of Miocene flint originating in the central area of the Iberian Peninsula.

All items were knapped following a similar technological procedure, with the aim of creating a spherical morphological outline and 4–6 active edges (i.e. high ridges, see Table 2 and Figs. 6–7) bearing 5–10% cortex. SSB n. 2 is the exception, bearing 40% cortical surface (Fig. 2). The tools were knapped in different sizes in order to examine whether the participants of the experiment choose tools of a certain size according to the size of their palm, or according to the size of the bone they are processing.

The participants first broke the bone to extract the marrow and finally crushed the epiphyses, which contain fat that can be obtained and consumed as well (Blasco et al. 2024). The skilled participants were the first to break the bones while the unskilled participants observed them, in order to get an impression of the technique used to extract bone marrow with the tool. Each participant processed different skeletal parts to examine the possible effect on the accumulation patterns of signs of wear developed on the tools and on the taphonomy of the bones.

The processed bones (n = 9) were in a fresh state. While studies show that in some cases in the Lower Paleolithic period bones underwent a process of drying, thus allowing for late consumption of the marrow (Blasco et al. 2019), the archaeological record of the early stages of the Paleolithic period shows that the bones were mostly fresh when broken (Blasco et al. 2013, Bunn 1983, Villa and Mahieu 1991). The bones were prepared by removing the periosteum using a flint flake. The experiment focused on hammerstone percussion, produced when the bone rests on an anvil and is hit with a stone ball, following patterns identified in the anthropological and archaeological record: Stone anvils were used in various Oldowan and Acheulian African sites (e.g. Olduvai Gorge, Melka Kunture, West Turkana, FLK Zinj: see Berthelet and Chavaillon 2004; Harmand 2009; Domínguez-Rodrigo and Barba 2006; Leakey 1971), as well as Levantine Acheulian sites (‘Ubeidiya and Latamne, Gesher Benot Yaacov, see Bar-Yosef and Goren-Inbar 1993; Clark 1967; Goren-Inbar et al. 2015). The application of

Table 2 Metric data of SSB replicas used for bone breaking

Replica no	Weight (gr)	No. of active edges (high ridges)
1	**1436**	6
2	**1265**	5
3	**673**	5
4	**1039**	6
5	**983**	4
6	**988**	5
7	**576**	4
8	**955**	6
9	**911**	6

Table 1 The skilled and unskilled participants in the experiment

Participant	Skill level	Gender	Hand palm measurements (cm)	SSB replica no	Processed bone
1 JR	High	M	Palm length: 11.4 Finger: 8.5 Width: 10.2	1, 9	Left cow femur Right pig femur
2 JBP	High	M	Palm length: 12 Finger: 8.8 Width: 10	4	Right cow femur
3 CT	Low	F	Palm length: 10.4 Finger: 8.8 Width: 7.8	6, 8	Right cow radius Left pig femur
4 ISA	Low	F	Palm length: 10.5 Finger: 8.5 Width: 8	3	Right Cow tibia
5 SAU	Low	M	Palm length: 11.2 Finger: 8.3 Width: 8.8	2, 7	Left cow tibia Right pig femur
6 MAR	Low	M	Palm length: 11 Finger: 7.5 Width: 9.3	5	Right cow radius

anvils in bone breaking was also observed ethnographically (Marlowe 2010; Yellen 1977;).

In this experiment, an anvil of 388 cm length, 172 cm width, and 140 cm thickness was used to stabilize the bone before hitting. During the test, the macro-tools were mainly used for crushing fresh bone using a repeated gesture of thrusting percussion. The time it took to break each bone, the identifying number of the experimental tool, and the identity of the experimenter were systematically recorded; additional documentation related to each experimenter was obtained using photos and videos.

Stage 2: (a) Taphonomic analysis The bones were analyzed by J.R. to identify possible indicative breakage patterns that might attest to the participants' skill level. The analytical approaches used in this study follow the established criteria for identifying bone breakage caused by human activity. These include various indicators such as percussion pits or percussion marks, percussion notches or conchoidal scars, impact flakes, adhering flakes, and counterblows, as outlined in prior works (e.g., Blumenschine and Selvaggio 1988; Capaldo and Blumenschine 1994; Pickering and Egeland 2006). Percussion notches are characterized by semicircular indentations on fracture edges accompanied by corresponding negative flake scars. Impact flakes are the resultant positive flakes from percussion notches and exhibit similar technical characteristics as stone flakes, typically featuring a ventral face with a point of detachment and bulb. Percussion pits (or percussion marks) often coincide with areas of striae, indicating the sliding of stone against bone during impact. The location and extent of percussion modifications were documented in relation to anatomical area, portion, and surface. The Study was done 'blind', without knowing who had created the set of fragmented bones.

(b) Traceological analysis Methods and criteria for identifying, describing, and interpreting macro- and micro-wear on stone tools were based on well-known literature in the field of functional studies of material culture (Adams 1993; Bofill 2012; Clemente Conte et al. 2015; DeBeaune 2004; Dubreuil et al 2015; Keeley 1980; Yustos et al. 2015). Use-wear traces preserved on the SSBs were analyzed at UAM by S. Perez. The SSB replicas were cleaned by immersion washing with deionized water and 10% TWEEN neutral soap for 20 min in an ultrasonic tank. In some cases, this was not sufficient, so a 20% solution of hydrogen peroxide (H2O2) and deionized water was applied for a variable time of 10–20 min in the ultrasonic tank to remove organic matter. After the cleaning process, the materials were observed using an Olympus DSX1000 high-resolution microscope with a 5 × objective.

Traces were described following the tribology-based variables proposed by Adams (1993), including the categories of fatigue (fracture, crack, pits) and abrasion (striation, leveling, grain edge rounding).

Results

The results will be presented according to the three stages listed above. First, impressions from the experiment itself will be shared, including aspects of tool handling and gripping as well as body postures and gestures of the participants (3.1). Then the results of the bone analysis will be presented (3.2a), followed by the traceological analysis of the SSB replicas (3.2b).

Skilled vs. unskilled use of SSBs for bone breaking

Skilled participants These participants (Table 3) tended to choose heavier implements and applied different degrees of force throughout the bone breaking process, depending on the stage. They applied great force for the initial opening of the bone, but applied gentler force for the extraction of the marrow itself to avoid contamination by tiny bone fragments. The skilled participants began the marrow extraction process by breaking the bone near its proximal end, in a thrusting percussion movement, rotating both the bone and the tool. They held the tool vertically at its proximal end and positioned it directly in the palm, with a gap between the thumb and the other fingers to ensure comfortable and stable positioning. They held the bone itself in the other hand with a gap between the thumb and the other fingers. The skilled participants sat with both legs folded, while leaning forward (Fig. 1). One participant used a flint flake throughout the extraction process to detach the bone from the marrow, therefore preventing the bone from breaking into it. For the crushing of the epiphyses, they used the flat surface of the implement (rather than the high ridges).

Unskilled participants These participants (Table 3) tended to sit with one leg folded back and one leg folded forward vertically, which made it difficult to control the intensity of the applied force and the accuracy of the blow (Fig. 2). One participant chose a tool that was too small for the task and thus uncomfortable to hold. The unskilled participants began by breaking the bone in the middle with a thrusting percussion movement. The unskilled participants held the tool while employing force with their fingertips to improve their grip, with a smaller gap between the thumb and the other fingers compared to the skilled participants (Fig. 2). They held the implement horizontally on its lateral side, and three participants occasionally held the tool with both hands. When they were unsuccessful in breaking the bone, they smashed the implement against it with both hands (Fig. 3), causing the bone to slip, and in some cases, they hurled the

Fig. 1 A skilled participant using SSB 1 to break the diaphysis and epiphysis of a cow bone. Notice the body posture (folded legs, leaning forward) and the handling of both the implement and the bone (in the palm, with a gap between the thumb and other fingers)

Fig. 2 Unskilled participants using SSBs to break the diaphysis and epiphysis of a bone. Notice the body posture (**a**, **b**), the hand holding the implement on its lateral side (**a**, **b**), and the small gap between the thumb and the other fingers holding the bone (**b**)

Fig. 3 Unskilled participants holding the implement with both hands and smashing it on the bone

Fig. 4 Unskilled participants holding the implement on its lateral side and applying force in the fingertips while holding the bone (middle and right). Notice the angle of the wrist of the hand holding the bone, compared to the skilled participant (left), holding the bone from below

Table 3 A comparison between skilled vs. unskilled participants

	High skill level	Low skill level
Location of breakage of the bone	Proximal end	Middle of the bone
Force applied	Modified throughout the process according to the stage	Mostly great force
Body posture	Sitting with both legs folded, leaning forward	One leg folded back and one leg folded forward vertically
Tool gripping	Entire palm Gap between the thumb and other fingers	Entire palm, sometimes with a small gap between the palm and the implement Smaller gap between the thumb and the other fingers
Tool handling	One hand From the top, vertically	Occasionally both hands (smashing or hurling) Occasionally from the side, horizontally
Bone handling	Entire palm Convex wrist Gap between the thumb and other fingers	Entire palm/ not handled Concave wrist Smaller gap between the thumb and the other fingers
Working areas of SSB	Bone breaking for marrow extraction: high ridges Epiphyses crushing: flat surface	Bone breaking for marrow extraction: high ridges Epiphyses crushing: flat surface

tool at the bone. While handling the bone, they tended to hold their wrists at a concave angle (Fig. 4). One participant hit the marrow itself while it was being exposed, resulting in tiny bone splinters penetrating within. The unskilled participants constantly tried to improve their grip. Similarly to the skilled participants, they used the flat surface of the implement (rather than the high ridges) to crush the epiphyses. Table 3 summarizes the main differences between skilled and unskilled participants.

The processed bones

Given that no specific instructions were given, all experimenters manipulated the bones intuitively, with individual-specific variations (see Blasco et al. 2013). The bones were generally held by the narrowest metaphysis and supported on the anvil by the side that provided greater stability: femurs and radiuses by their cranial side and tibias by one of their lateral sides. Therefore, most of the marks were generated on the same sides and portions. Subsequent analyses revealed a certain diversity in the generated marks, which could be related to the experience of each researcher as well as other factors such as physical characteristics (strength, hand size, percussors, etc.) and the type of bone. This diversity of marks, as well as the quantity, increased among less experienced experimenters. In some bones of the smaller animals (pig), the multiple overlapped notches with some adhering flakes and the generalized smashing of metaphysis showed an insistence on fracture processes. On the other hand, more experienced individuals barely left diagnostic signs of anthropogenic fracture. The bones were opened from longitudinal cracks, and only in one case a percussion pit was observed. Large bones (cow) left a greater number of notches, both consecutive and overlapping. Their number decreased as the level of experience of the individuals increased (between 4 and 5 among the less experienced and between 2 and 3 among the most experienced). This greater number of notches among the less experienced was associated with other marks, such as areas with multiple percussion pits and smashing of the metaphysis (Table 4). Although, in this case, the available data may seem insufficient to achieve significant statistical results, they show similar trends to previous experiments conducted with this specific aim (see Blasco et al. 2013, 2014).

Traceological analysis of SSB replicas

A variety of macro-and micro-wear traces were observed on the SSB replicas, which are consistent with characteristics expected from hard contact between the tools and fresh bone in thrusting percussion activity. Overall, micro-flake detachments and leveled areas were observed at 20x–50× magnification on 9 items: SSBs covered with limestone cortical surfaces show trapezoidal fractures, while the fractures of the flint SSBs that do not bear cortical surface are irregular. For the observation of the polish, a Leica DMRX metallographic microscope with reflected light equipped with 10× eyepieces and 5x, 10x, 20× and 40× objectives, coupled with a ZEISS Axiocam 208 colour camera with 4 K resolution and panoramic vision, was used. The prominent feature observed was the cracking of the surface in the form of cascade of step scars and the scarce presence of polish. Macro-striations were observed on 7 items. Macro-traces of splintering were localized on the prominent ridges of the tools, which appeared as rounded at 10× magnification. The macro-detachments were produced by repeated and continuous contact with a hard material, but they did not lead to significant changes in the original SSB morphology. They characterize all replicas used by both the skilled and unskilled participants (Figs. 5, 6, 7 and 8).

However, two distinct patterns were observed that indicate certain differences between skilled and unskilled participants were observed – these concern the intensity of the percussion traces and their distribution. Tools used by skilled participants exhibited more intense traces that were concentrated in specific locations on the implement. In contrast, tools used by unskilled participants exhibited impact fractures that were weaker but more widely dispersed along the prominent ridges of the implement, as these participants tended to rotate the tool more often, constantly trying to improve their grip (Fig. 8).

The fact that different parts of the skeleton were worked by the participants did not affect the accumulation of signs of use in terms of variety and intensity.

Discussion

In this paper, we examined aspects of skill related to the use of shaped stone balls as percussion tools, through an experimental study. Tool use is not only influenced by planning and functions related to the final target of the action, but has an intrinsic and fundamental component associated with haptics and sensing (Kappers and Bergmann Tiest 2013). Accordingly, action and perception are deeply integrated, and must be intended as a single functional system (Ackerley and Kavounoudias 2015). It was assumed, in the past, that human thought takes place as an internal computational process, and therefore the archaeological record is an external product or a behavioral trace of this process (Wynn et al. 2021). Current approachs to human cognition, such as The 4E approach, states that even during the LP, 'hominin thinking literally played out through their hands and tools' (Wynn et al. 2021:99). Cognition is the interaction between the brain, body, and the world. Thus, the archaeological record is an integral part of the thinking process, as are stone tools: 'Their cutting edge is in fact material extension of hominin action that restructured their mental engagement with the material world' (Wynn et al. 2021: 103)". The resulting structural relationship between brain, body, and tool is, furthermore, extremely plastic, and manipulative training can lead to neural adjustments in a few weeks, even in non-human primates (Quallo et al. 2009). Indeed, it has been hypothesized that the pronounced complexity

Table 4 Summary of the main characteristics and variables taken into account during the bone breakage process in each experimental series

Exp	Taxon	Element	Notches	Relation	Side	Portion	Flakes	Count	Pits	Other	Participants skill
1	Cow	Femur left	2	conseq	caudal	prox.-medial	2	1			High
1	Pig	Femur right								Long. Crack	High
2	Cow	Femur right	3	overlapped	caudal	prox.-medial	1				High
3	Pig	Femur right							1 isol	Long. Crack	Low
3	Cow	Radius right	2	overlapped	caudal	medial			1 area	Smashed prox. metaph	Low
4	Cow	Tibia right	2	conseq	medial	medial	1	1	1 area		Low
5	Cow	Tibia left	4	overlapped	medial	medial	3			Smashed prox. metaph	Low
5	Pig	Femur left	1	isol	caudal	medial		1		Long. Crack	Low
6	Cow	Radius right	5	overlapped	caudal	prox.-medial	3		2 areas	Smashed prox. metaph	Low

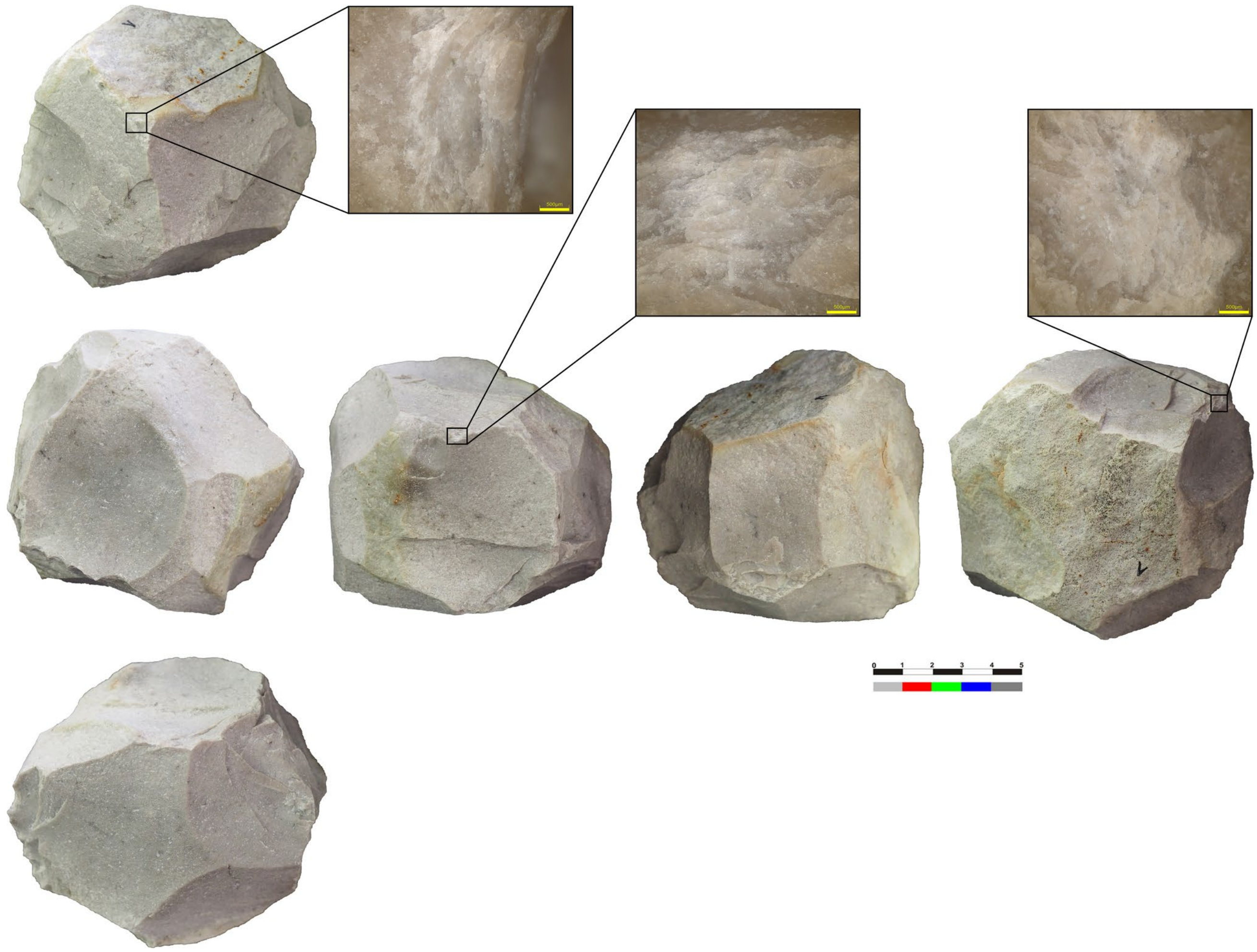

Fig. 5 SSB N. 1. used by a skilled participant. High, intersecting ridges were used to break the bone diaphysis, producing step-shaped longitudinal crushing along the active edges and the rounding of these areas

of the human parietal cortex might have been associated with an increasing capacity in integrating tools into the body schemes, enhancing the interplay between sensing and cognition (Bruner 2021; Bruner et al. 2018). Tool sensing and tool use, as opposed to skill in stone making, has yet to be comprehensively explored.

Ethnographic observations of contemporary indigenous societies indicate that gaining skill and accumulating knowledge related to tools is a complex, holistic process; it includes knowledge of the shaping process and knowledge of how to use the tool. These aspects are inseparable. Learning how to use a tool sometimes precedes and even contributes to the successful learning of its shaping process. Among the Baka of southeastern Cameroon, through peer group participation, children learn to use increasingly complex tools (Gallois et al. 2015). Sonoda (2016) describes collective hunting, gathering, and other cultural activities such as butchering animals, in which adults and adolescents are frequently helped by children. For example, game is butchered primarily by male adolescents, who are often observed and helped by younger children as part of the learning process, which allows children to establish their autonomy (Lew-Levy et al. 2018). BaYaka children learn tool use activities first by imitating and observing older children and adults, and later mostly by practicing. By middle childhood, BaYaka girls are already digging yams and using machetes efficiently (Salali et al. 2019). Among the South African San, children have access to a vast number of tools from which they can choose to practice and play with. They are shown how to make tools and are capable of producing and using them (Nielsen et al. 2014). Similar patterns were observed in south Ethiopian agricultural communities that are based upon a craft specialization system, which includes both production and use of tools (Arthur 2010, 2018; Brandt and Weedman 1997; Gallagher 1974). These learning processes leave their visible marks on both the tool and the processed material (Egeland et al. 2014; Ingold 2001). However, we lack experimental data that could contribute to our reading

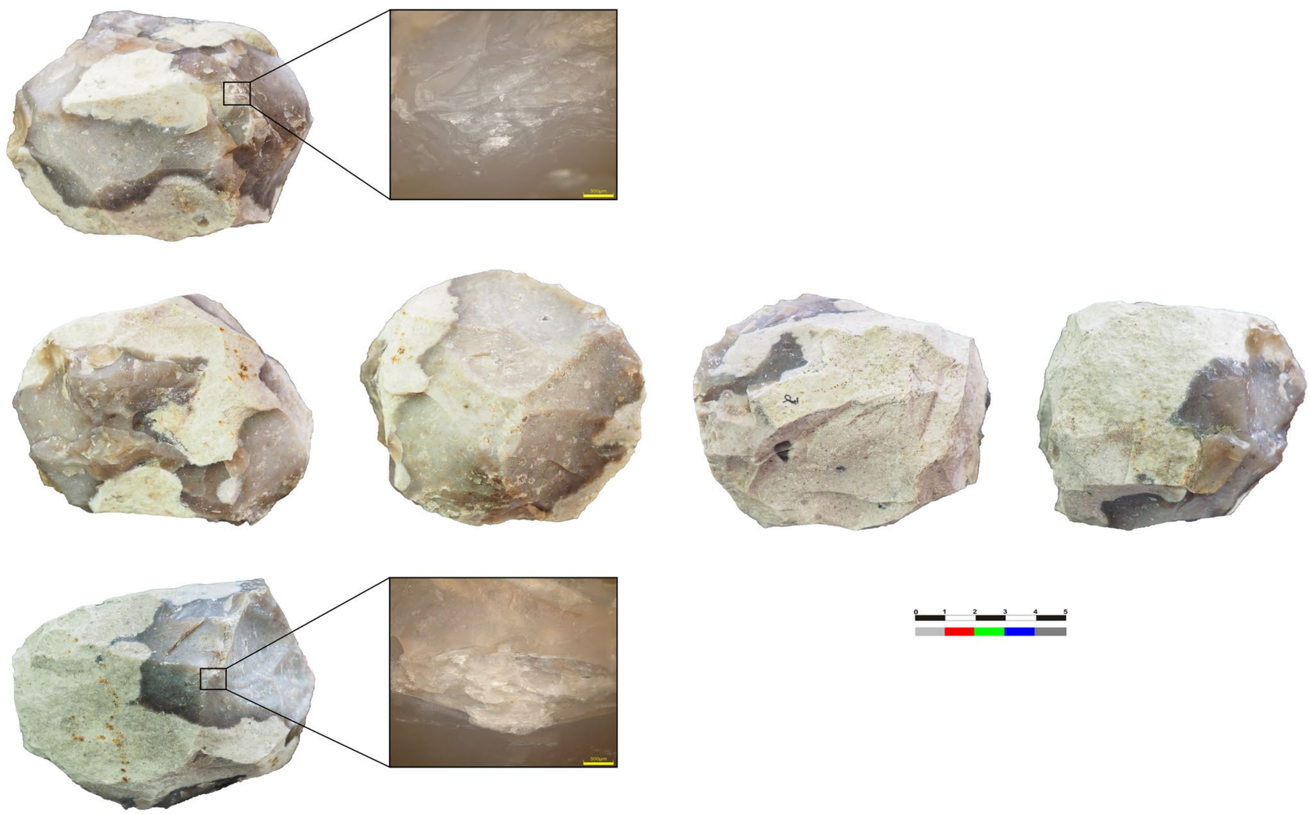

Fig. 6 SSB N.2. The presence of cortex in this SSB reduced the percussive areas but favored the creation of a prehensile area. The limestone parts provided comfortable gripping because they were not as sharp. Rounding and splintering of the active area were detected

of the archaeological record and the identification of these learning processes in the Paleolithic culture.

Here, we focused on percussive artefacts used for bone breaking – one of the most common activities of the LP – with the goal of better understanding aspects of skill related to LP tool use through experimental- tracecological approach.

The distinction between wear traces that developed under different circumstances—as a result of different activities, functions, or skill levels– is a complicated task. That being said, studies focusing on these issues in recent years show that a techno-traceological approach greatly advances our understanding of the accumulation of different types of wear traces and the circumstances leading to their formation (see, for example Julien et al. 2014; Karlin et al. 1990; Karlin 1991; Karlin and Julien 2019; Leroi-Gourhan and Brezillon 1966; Torres Navas 2022).

Previous archaeological and experimental studies have shown that percussion activities and specifically bone breaking leaves characteristic marks, compared to plant pounding and meat-tenderizing (see Mora and de la Torre 2005; De la Torre et al 2013; Yustos et al. 2015 for further discussion). Multi percussive elements were shown to develop extreme wear traces in terms of incidence, distribution, density, use intensity and interaction intensity (Yustos et al. 2015). However, the analysis of use traces developed on percussive artefacts following skill patterns has hardly been documented. This was our main goal.

The results of this study give rise to several interesting insights. First, while we tend to think that bone-breaking is intuitive, it requires planning, knowledge of bone anatomy and tool use, as well as skill and experience. When we compared how skilled versus unskilled users extracted marrow from the bone, we saw differences in how the bone and the tools were gripped and in the intensity of the force applied throughout the process. These differences stem from the knowledge, or lack thereof, of the anatomy of the bone itself and its fracture patterns. Additionally, the user must also know how to choose the right tool for the task. The chosen tool should fit comfortably in the user's hand, affording precise grip and handling, as if the tool were an extension of the body, which must also be positioned precisely when applying force to the bone. As was recently shown, hand size has no straightforward importance, and accordingly, there is an intrinsic variability in the patterns of grasping, depending on individual factors (Fedato et al. 2024).

It is interesting to note that similar patterns were observed with regards to knapping; it has been experimentally

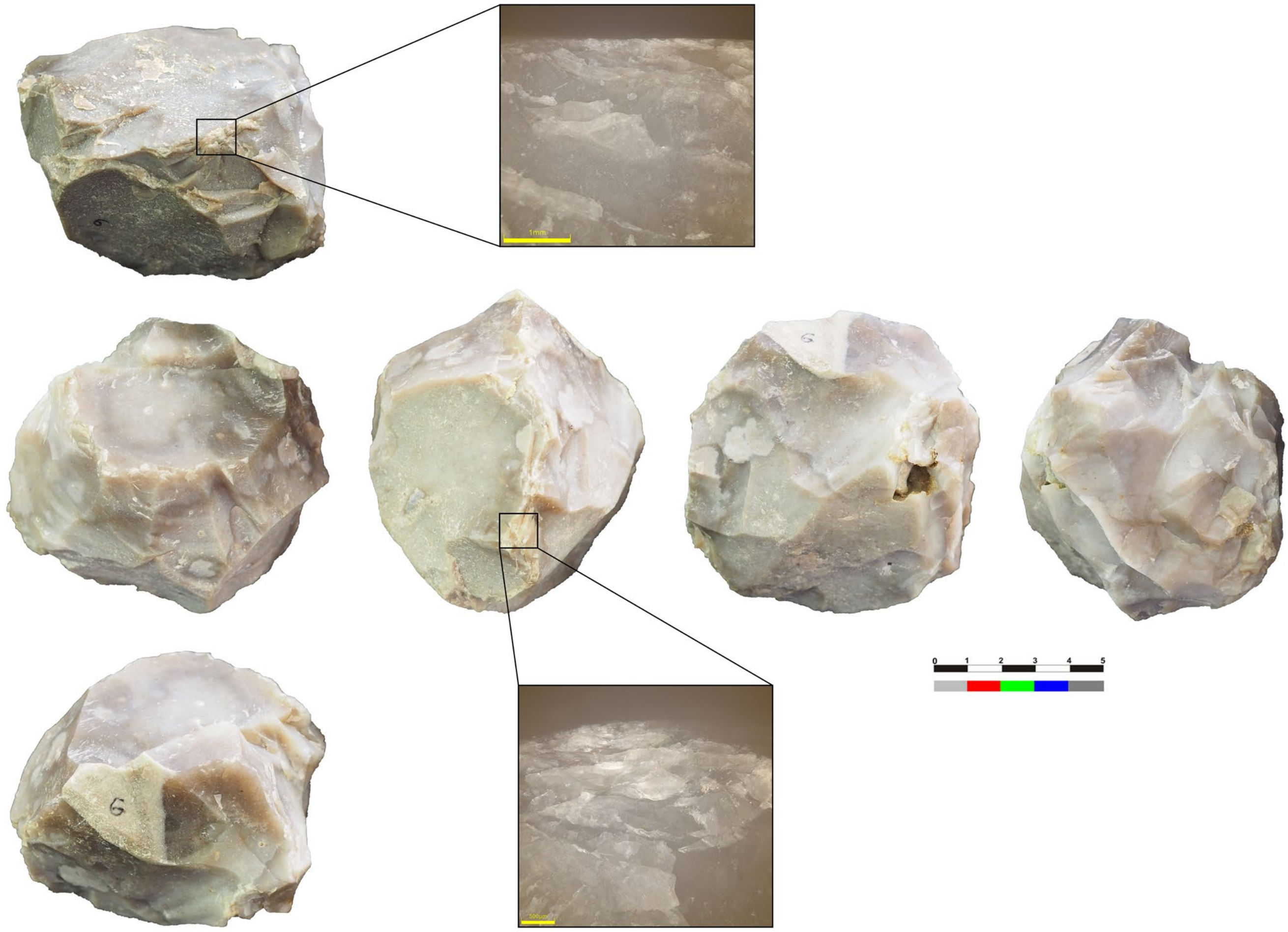

Fig. 7 SSB N. 6. used by an unskilled participant. The small concentric circles (marked with a black squares) signify impact with a hard material due to the contact of the spheroid with the hard surface that supports the bone

demonstrated that expert knappers use lower force to increase their precision of striking (Dapena, et al. 2006; Nonaka et al. 2010; Rein et al. 2013), which could be an indicator of greater accuracy and the need for fewer rotations of the piece. The significant role of the thumb in the grip was further emphasized by Key and Dunmore (2015), showing it was recruited significantly more frequently and experienced significantly greater manipulative forces during core repositioning events and the securing of the core during flake detachments. Our study further supports these observations, showing that (1) unskilled breakers constantly rotated the tool whereas skilled participants had a more stable grip. The thumb, and the gap between it to the other fingers, played a significant role in this aspect. (2) skilled participants had to hit the bone fewer times to break it. Although they applied greater force in the preliminary stage, they later applied gentler force for the extraction of the marrow itself to avoid contamination by tiny bone fragments, indicating more accurate use of the implement (a pattern similarly observed by De la Torre et al 2013).

These observed differences in body posture, gestures, tool gripping, and handling of skilled versus unskilled participants influenced the intensity and dispersion of wear traces on the tools. Tools used by unskilled participants developed weaker and more widespread traces, while tools used by skilled participants developed stronger but concentrated traces. These results are in accordance with Ingold's claim that an unskilled user has an unskilled body (2001). Thus, when examining use-wear traces on the archeological tools, skill should also be taken into account.

Moreover, differences were also detected with regard to the processed bones: the diversity of marks, as well as the quantity, increased among less experienced experimenters. This diversity could be related to a less controlled breaking of the bone and less accurate use of the tool, while smashing the bone rather than breaking it accurately.

Both skilled and unskilled participants intuitively used the high intersecting ridges of the implement to break the bone for marrow extraction and the flat surfaces to crush the epiphyses, in order to extract the fat. This tool was shown

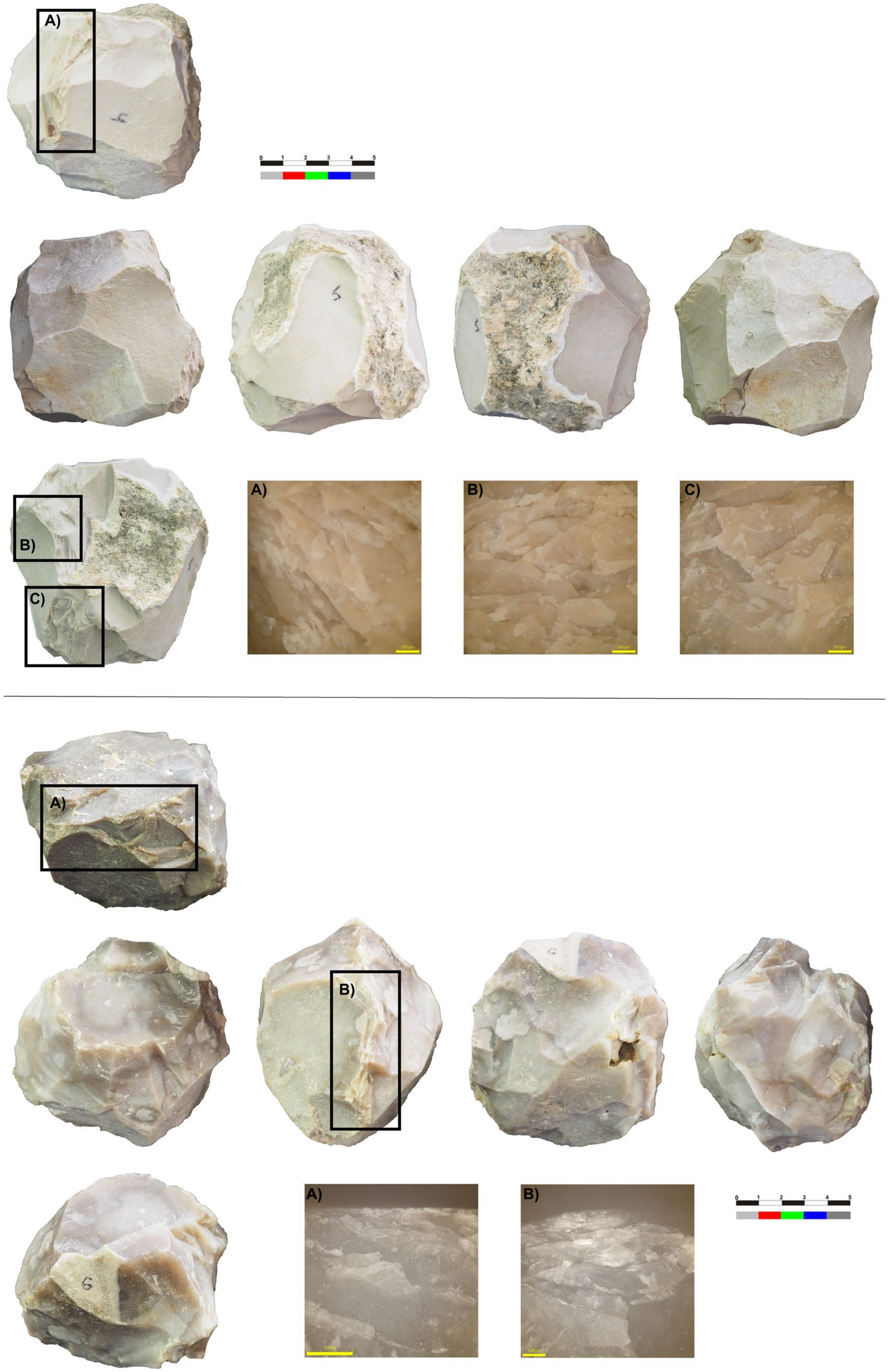

Fig. 8 SSB N. 4 and 6. Replica used by skilled participant (up), showing stronger yet fewer traces, compared to unskilled participant (down), showing weaker but more widespread traces

to be efficient for both purposes. Archaeological SSBs bear functional traces on the high ridges as well as on the flat surfaces (Assaf et al. 2020; Blasco et al. 2024), which might attest to their use for both purposes in the LP.

It should be noted that in this study we chose to examine two skill levels degrees—skilled versus unskilled—in order to identify clear differences between experienced and inexperienced individuals using the tools. The archaeological record likely reflects different levels of skill, including intermediate levels, as unskilled individuals were probably exposed to marrow extraction activities on a daily basis and therefore acquired their knowledge and skill gradually. Therefore, more complex patterns are expected to be discovered when analyzing archaeological contexts.

Moreover, apart from the skill of the user, efficient breaking of the bone is also a function of the morphology and other characteristics of the tool itself – the number of active edges, the percentage of cortex present on the surface, symmetry, and so on (see Key and Lycett 2017; Lycett et al. 2016; Machin et al. 2007 with regards to handaxes). The quality and characteristics of the stone may also have a potential effect, although our previous experiments showed that flint, dolomite and limestone SSBs were all efficient for bone breaking (Assaf and Baena 2022).

Conclusions

In their study from 2018, Key et al. demonstrated how grip is a matter of choice; it varies according to the type and form of the stone tool used and tool-use contexts. This study is aimed at exploring the influence of experience and skill on this choice when using percussion tools. Stable and precise handling and grip, which have been observed in skilled individuals, may lead to efficient use of the tool, and therefore to efficient processing of the material. Ultimately, these aspects have a visible expression on material culture, as skill can determine a traceological distribution on artifacts. Hopefully, these insights can form a basis for further experimental studies, and eventually contribute to a better understanding of the Lower Paleolithic record.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval All procedures performed were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all the individual participants included in the study.

Publication consent Publication consent was obtained from all individual participants included in the study.

Disclosures and declarations The authors declare they have no financial interests.

Competing interests The authors declare no competing interests.

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References

Ackerley R, Kavounoudias A (2015) The role of tactile afference in shaping motor behaviour and implications for prosthetic innovation. Neuropsychologia 79:192–205

Adams JL (1993) Mechanisms of wear on ground stone surfaces. Pac Coast Archaeol Soc Q 29(4):61–74

Arthur KW (2010) Feminine knowledge and skill reconsidered: Women and flaked stone tools. Am Anthropol 112(2):228–243

Arthur KW (2018) The lives of stone tools: Crafting the status, skill, and identity of flintknappers. University of Arizona Press

Arroyo A, de la Torre I (2020) Pitted stones in the Acheulean from Olduvai Gorge Beds III and IV (Tanzania): a use-wear and 3D approach. J Hum Evol 145:102837

Assaf E (2021a) Throughout the generations: Learning processes and knowledge transmission mechanisms as reflected in lithic assemblages of the terminal Lower Paleolithic Levant. J Archaeol Sci Rep 35:102772

Assaf E (2021b) Dawn of a new day: The role of children in the assimilation of new technologies throughout the Lower Paleolithic. Anthropologie 125(1):102836

Assaf E (2024) Set in Stone: Human-Horse Relations as Embodied in Shaped Stone Balls. Archaeologies 20(1):64–105

Assaf E, Baena J (2022) Raw material selectivity in Lower Paleolithic shaped stone ball production: experimental research. Archaeol Anthropol Sci 14(1):24

Assaf E, Caricola I, Gopher A, Rosell J, Blasco R, Bar O et al (2020) Shaped stone balls were used for bone marrow extraction at Lower Paleolithic Qesem Cave Israel. Plos One 15(4):e0230972

Assaf E, Baena Preysler J, Bruner E (2023a) Lower Paleolithic Shaped Stone Balls—What Is Next? Some Cultural-Cognitive Questions. Quaternary 6(4):51

Assaf E, Nunziante-Cesaro S, Gopher A, Venditti F (2023b) Learning by doing: investigating skill through techno-functional study of recycled lithic items from Qesem Cave (Israel). J Archaeol Method Theory 30(1):64–102

Bamforth DB, Finlay N (2008) Introduction: archaeological approaches to lithic production skill and craft learning. J Archaeol Method Theory 15:1–27

Barkai R, Gopher A (2016) On anachronism: the curious presence of spheroids and polyhedrons at Acheulo–Yabrudian Qesem Cave, Israel. Quat Int 398:118–128

Barsky D, Vergès JM, Sala R, Menéndez L, Toro-Moyano I (2015) Limestone percussion tools from the late early Pleistocene sites of Barranco León and Fuente Nueva 3 (Orce, Spain). Philos Trans R Soc Lond B Biol Sci 370(1682):20140352

Bar-Yosef O, Goren-Inbar N (1993) The lithic assemblages of ʻUbeidiya (Qedem 34). Institute of Archaeology, Hebrew University, Jerusalem, Israel

Ben-Dor M, Sirtoli R, Barkai R (2021) The evolution of the human trophic level during the Pleistocene. Am J Phys Anthropol 175:27–56

Berthelet A, Chavaillon J (2004) Prehistoric archaeology. The site of Karre I. In: Chavaillon J, Piperno M (eds) Studies on the early Paleolithic site of Melka Kunture, Ethiopia. Florence, Italy: Istituto Italiano di Preistoria e Protostoria, p 211–251

Blasco R, Rosell J, Domínguez-Rodrigo M, Lozano S, Pastó I, Riba D et al (2013) Learning by heart: cultural patterns in the faunal processing sequence during the Middle Pleistocene. PLoS ONE 8(2):e55863

Blasco R, Domínguez-Rodrigo M, Arilla M, Camarós E, Rosell J (2014) Breaking bones to obtain marrow: a comparative study between percussion by batting bone on an anvil and hammerstone percussion. Archaeometry 56(6):1085–1104

Blasco R, Rosell J, Sanudo P, Gopher A, Barkai R (2016) What happens around a fire: faunal processing sequences and spatial distribution at Qesem Cave (300 ka), Israel. Quatern Int 398:190–209

Blasco R, Rosell J, Arilla M, Margalida A, Villalba D, Gopher A, Barkai R (2019) Bone marrow storage and delayed consumption at Middle Pleistocene Qesem Cave, Israel (420 to 200 ka). Sci Adv 5(10):eaav9822

Blasco R, Rosell J, Assaf E, Barkai R, Gopher A (2024) Exploring the lack of articular ends at the Middle Pleistocene site of Qesem Cave. Israel J Hum Evol 189:103509

Bleed P (2008) Skill Matters. J Archaeol Method Theory 15:154–166

Blumenschine RJ (1995) Percussion marks, tooth marks, and experimental determinations of the timing of hominid and carnivore access to long bones at FLK Zinjanthropus, Olduvai Gorge Tanzania. J Hum Evol 29(1):21–51

Blumenschine RJ, Selvaggio MM (1988) Percussion marks on bone surfaces as a new diagnostic of hominid behaviour. Nature 333(6175):763–765

Blumenschine RJ, Prassack KA, Kreger CD, Pante MC (2007) Carnivore toothmarks, microbial bioerosion, and the invalidation of Dominguez-Rodrigo and Barba's (2006) test of Oldowan hominin scavenging behavior. J Hum Evol 53:420–426

Bofill M (2012) Quantitative analysis of use-wear patterns: a functional approach to the study of grinding stones. In: Broadening horizons 3: Conference of young researchers working in the Ancient Near East. Servicio de Publicaciones, p 63–84

Bonnichsen R (1973) Some operational aspects of human and animal bone alteration. In: Gilbert BM (ed) Mammalian osteoarchaeology: North America. Missouri Archaeological Society, Columbia, pp 9–24

Bourguignon L, Barsky D, Ivorra J, De Weyer L, Cuartero F, Capdevila R et al (2016) The stone tools from stratigraphical unit 4 of the Bois-de-Riquet site (Lézignan-la-Cèbe, Hérault, France): a new milestone in the diversity of the European Acheulian. Quat Int 411:160–181

Brandt SA, Weedman K (1997) The ethnoarchaeology of hide working and flaked stone tool use in southern Ethiopia. Ethiopia in broader perspective (Kyoto, 12–17 December 1997), p 351–361

Bril B, Smaers J, Steele J, Rein R, Nonaka T, Dietrich G,..., Roux V (2012) Functional mastery of percussive technology in nut-cracking and stone-flaking actions: experimental comparison and implications for the evolution of the human brain. Philosophical Transact Royal Soc B: Biol Sci 367(1585):59–74

Bruner E (2021) Evolving human brains: paleoneurology and the fate of Middle Pleistocene. J Archaeol Method Theory 28:76–94

Bruner E, Fedato A, Silva-Gago M, Alonso-Alcalde R, Terradillos-Bernal M, Fernández-Durantes MÁ, Martín-Guerra E (2018) Visuospatial integration and hand-tool interaction in cognitive archaeology. Curr Top Behav Neurosci 41:13–36

Bunn HT (1981) Archaeological evidence for meat-eating by Plio-Pleistocene hominids from Koobi Fora and Olduvai Gorge. Nature 291(5816):574–577

Bunn HT (1983) Comparative analysis of modern bone assemblages from a San hunter-gatherer Camp in the Kalahari Desert, Botswana, and from a spotted hyena den near Nairobi, Kenia. In: Clutton-Brock J, Grigson C (eds) Animals and Archaeology: 1. Hunters and Their Prey. Oxford: British Archaeological Reports International Series 163:143–148

Cabanès J, Borel A, Baena Preysler J, Lourdeau A, Moncel MH (2022) Palaeolithic polyhedrons, spheroids and bolas over time and space. PLoS ONE 17(7):e0272135

Cabanès J, Borel A, Preysler JB, Cliquet D, Colonge D, Moncel MH (2024) What function(s) for Palaeolithic polyhedrons, spheroids and bolas? Cases from France and North Africa Archaeol. Anthropol Sci 16(5):1–51

Capaldo SD (1997) Experimental determinations of carcass processing by Plio-Pleistocene hominids and carnivores at FLK 22 (Zinjanthropus), Olduvai Gorge Tanzania. J Hum Evol 33(5):555–597
Capaldo SD, Blumenschine RJ (1994) A quantitative diagnosis of notches made by hammerstone percussion and carnivore gnawing on bovid long bones. Am Antiq 59(4):724–748
Carvalho S, Beardmore-Herd M, Carvalho S, Beardmore-Herd M (2019) Technological origins: primate perspectives and early hominin tool use in Africa. Oxford Research Encyclopedia of African History, (March), 1–27
Clark JD (1967) The Middle Acheulian occupation site at Latamne, Northern Syria (1st paper). Quaternaria 9:1–68
Clark JD (1982) The cultures of the middle Palaeolithic/Middle stone age. Camb Hist Afr 1:248–341
Clemente Conte I, Lazuén Fernández T, Astruc L, Rodríguez Rodríguez AC (2015) Use-wear analysis of nonflint lithic raw materials: The cases of quartz/quartzite and obsidian. Use-wear and residue analysis in archaeology, p 59–81
Corvinus-Karve G (1968) An Acheulian occupation floor at Chirki-on-Pravara India. Curr Anthropol 9(2–3):216–218
Dapena J, Anderst WJ, Toth NP (2006) The biomechanics of the arm swing in Oldowan stone flaking. The Oldowan: Case Studies into the Earliest Stone Age, p 333–338
Dart RA (1959) Further light on australopithecine humeral and femoral weapons. Am J Phys Anthropol 17(2):87–93
De la Torre I, Benito-Calvo A, Arroyo A, Zupancich A, Proffitt T (2013) Experimental protocols for the study of battered stone anvils from Olduvai Gorge (Tanzania). J Archaeol Sci 40(1):313–332
De Weyer L (2017) An Early Stone Age in Western Africa? Spheroids and polyhedrons at Ounjougou, Mali. J Lithic Stud. 4(1)
DeBeaune S (2004) The invention of technology: prehistory and cognition. Curr Anthropol 45(2):139–162
Domínguez-Rodrigo M, Barba R (2006) New estimates of tooth mark and percussion mark frequencies at the FLK Zinj site: the carnivore-hominid-carnivore hypothesis falsified. J Hum Evol 50(2):170–194
Dubreuil L, Savage D, Delgado-Raack S, Plisson H, Stephenson B, de la Torre I (2015) Current analytical frameworks for studies of use–wear on ground stone tools. In: Marreiros JM, Gibaja Bao JF, Bicho NF (eds) Use-wear and residue analysis in archaeology. Springer, Cham, pp 105–158
Egeland CP, Welch KR, Nicholson CM (2014) Experimental determinations of cutmark orientation and the reconstruction of prehistoric butchery behavior. J Archaeol Sci, p 126–133
Fedato A, Silva-Gago M, Terradillos-Bernal M, Alonso-Alcalde R, Bruner E (2024) The influence of hand dimensions on finger flexion during Lower Paleolithic stone tool use in a comfortable grip. Quaternary 7:29
Ferraro JV, Plummer TW, Pobiner BL, Oliver JS, Bishop LC, Braun DR, Potts R (2013) Earliest archaeological evidence of persistent hominin carnivory. PloS One 8(4):e62174
Finlay N (2008) Blank concerns: issues of skill and consistency in the replication of Scottish Later Mesolithic blades. J Archaeol Method Theory 15:68–90
Gallagher JP (1974) The preparation of hides with stone tools in South Central Ethiopia. J Ethiop Stud 12(1):177–182
Gallois S, Duda R, Hewlett B, Reyes-García V (2015) Children's daily activities and knowledge acquisition: A case study among the Baka from southeastern Cameroon. J Ethnobiol Ethnomed 11:1–13
García-Vadillo FJ, Canals-Salomó A, Rodríguez-Álvarez XP, Carbonell-Roura E (2022) The large flake Acheulean with spheroids from Santa Ana Cave (Cáceres, Spain). J Archaeol Sci Rep 41:103265
Geraads D, Hublin J, Jaeger JJ, Tong H, Sen S, Toubeau P (1986) The Pleistocene hominid site of Ternifine, Algeria: New results on the environment, age, and human industries. Quat Res 25(3):380–386
Geribàs N, Mosquera M, Vergès JM (2010) What novice knappers have to learn to become expert stone toolmakers. J Archaeol Sci 37(11):2857–2870
Gifford-Gonzalez D (2018) Human, Animal, Geological Causes of Bone Breakage. An introduction to Zooarchaeology. Springer, Cham, pp 203–224
Goren-Inbar N, Sharon G, Alperson-Afil N, Herzlinger G (2015) A new type of anvil in the Acheulian of Gesher Benot Ya 'aqov, Israel. Philos Trans R Soc Lond B Biol Sci 370(1682):20140353
Harmand S (2009) Raw materials and techno-Economic behaviors at Oldowan and Acheulean sites in the West Turkana region, Kenya. In: Adams B, Blades BS (eds) Lithic materials and paleolithic societies. Wiley-Blackwell, Oxford, UK, pp 3–14
Herzlinger G, Goren-Inbar N, Grosman L (2017) A new method for 3D geometric morphometric shape analysis: The case study of handaxe knapping skill. J Archaeol Sci Rep 14:163–173
Högberg A (2008) Playing with flint: tracing a child's imitation of adult work in a lithic assemblage. J Archaeol Method Theory 15(1):112–131
Ingold T (2001) Beyond art and technology: The anthropology of skill. In: Schiffer MB (ed.) Anthropological perspectives on technology. University of New Mexico Press, p 17–31
Isaac B (1987) Throwing and human evolution. Afr Archaeol Rev 5(1):3–17
Isaac GL, Isaac B (1977) Olorgesailie: archeological studies of a Middle Pleistocene lake basin in Kenya. (No Title)
Jones PR (1994) Results of experimental work in relation to the stone industries of Olduvai Gorge. In: Leakey MD, Roe DA (eds) Olduvai Gorge vol. 5. Cambridge: Cambridge University Press
Julien M, Karlin C, Allenet de Ribemont G (2014) Un automne à Pincevent : le campement magdalénien du niveau IV20
Kappers AM, Bergmann Tiest WM (2013) Haptic perception Wiley Interdisciplinary Reviews. Cogn Sci 4(4):357–374
Karlin C, Bodu P, Ploux S (1990) Who´s who? The Magdalenian flintknappers of Pincevent, France. In: Cziesla, E. (ed.) The big puzzle: International symposium on refitting stone artefacts, Moneros, 1987. Holos, Bonn, p 143–163
Karlin C, Julien M (2019) An autumn at Pincevent (Seine-et-Marne, France): Refitting for an ethnographic approach of a Magdalenian settlement. Archaeol Anthropol Sci 11:4437–4465
Karlin C (1991) Analyse d'un processus technique : le debitage laminaire des magdaleniens de pincevent (seine et marne). Treballs d'Arqueologia, p 0125–0161
Keeley LH (1980) Experimental determination of stone tool uses: A microwear analysis. University of Chicago Press
Key AJ, Dunmore CJ (2015) The evolution of the hominin thumb and the influence exerted by the non-dominant hand during stone tool production. J Hum Evol 78:60–69
Key AJ, Lycett SJ (2017) Influence of handaxe size and shape on cutting efficiency: a large-scale experiment and morphometric analysis. J Archaeol Method Theory 24:514–541
Key A, Merritt SR, Kivell TL (2018) Hand grip diversity and frequency during the use of Lower Palaeolithic stone cutting-tools. J Hum Evol 125:137–158
Kuman K, Field AS, Thackeray JF (1997) Discovery of new artefacts at Kromdraai. S Afr J Sci 93:187–193
Langley MC (2020) Space to play: Identifying children's sites in the Pleistocene archaeological record. Evol Hum Sci 2:e41
Le Tensorer JM, von Falkenstein V, Le Tensorer H, Schmid P, Muhesen S (2011) Étude préliminaire des industries archaïques

de faciès Oldowayen du site de Hummal (El Kowm, Syrie centrale). Anthropologie 115(2):247–266

Leakey LSB (1931) The Stone Age cultures of Kenya colony. Cambridge University Press, Cambridge

Leakey MD (1971) Excavations in Beds I and II, 1960–1963. Olduvai Gorge, Vol. 3. Cambridge: Cambridge University Press

Leroi-Gourhan A, Brezillon M (1966) L'habitation magdalénienne n° 1 de Pincevent près Monterau (Seine-et-Marne). Gallia Préhistoire 9:263–385. https://doi.org/10.3406/galip.1966.1264

Lew-Levy S, Lavi N, Reckin R, Cristóbal-Azkarate J, Ellis-Davies K (2018) How do hunter-gatherer children learn social and gender norms? A Meta-Ethnographic Review. Cross-Cult Res 52(2):213–255

Li X, Ao H, Dekkers MJ, Roberts AP, Zhang P, Lin S et al (2017) Early Pleistocene occurrence of Acheulian technology in North China. Quat Sci Rev 156:12–22

Lycett SJ, Schillinger K, Eren MI, von Cramon-Taubadel N, Mesoudi A (2016) Factors affecting Acheulean handaxe variation: Experimental insights, microevolutionary processes, and macroevolutionary outcomes. Quat Int 411:386–401

Machin AJ, Hosfield RT, Mithen SJ (2007) Why are some handaxes symmetrical? Testing the influence of handaxe morphology on butchery effectiveness. J Arch Sc 34(6):883–893

Malafouris L (2010) The brain–artefact interface (BAI): a challenge for archaeology and cultural neuroscience. Soc Cogn Affect Neurosci 5(2–3):264–273

Maloney TR (2019) Towards quantifying teaching and learning in prehistory using stone artifact reduction sequences. Lithic Technol 44(1):36–51

Marder O, Milevski I, Rabinovich R (2007) Revadim quarry. Hadashot Arkheologiyot Excav Surv Isr 119:1–20

Marlowe FW (2010) The Hadza: hunter-gatherers of Tanzania. University of California Press, Berkeley, CA

Mora R, De la Torre I (2005) Percussion tools in Olduvai Beds I and II (Tanzania): implications for early human activities. J Anthropol Archaeol 24(2):179–192

Muller A, Barsky D, Sala-Ramos R, Sharon G, Titton S, Vergès JM, Grosman L (2023) The limestone spheroids of 'Ubeidiya: intentional imposition of symmetric geometry by early hominins? R Soc Open Sci 10(9):230671

Nichols J, Allstadt DJ (1978) Hinge fracture rates of novice flintknappers. Lithic Technol 7(1):1–2

Nielsen M, Tomaselli K, Mushin I, Whiten A (2014) Exploring tool innovation: A comparison of Western and Bushman children. J Exp Child Psychol 126:384–394

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):155–167

Outram AK (2001) A new approach to identifying bone marrow and grease exploitation: why the "indeterminate" fragments should not be ignored. J Archaeol Sci 28(4):401–410

Paddayya K (1977) The Acheulian Culture of the Hunsgi Valley (Shorapur Doab) Peninsular India. Proc Am Philos Soc 121(5):383–406

Pelegrin J (1990) Prehistoric lithic technology: some aspects of research. Archaeol Rev Camb 9(1):116–125

Pickering TR, Egeland CP (2006) Experimental patterns of hammerstone percussion damage on bones: implications for inferences of carcass processing by humans. J Arch Sci 33(4):459–469

Pigeot N (1990) Technical and social actors. Flintknapping specialists and apprentices at Magdalenian Etiolles. Archaeol Rev Camb 9(1):126–141

Piperno M et al (2009) Obsidian exploitation and utilization during the Oldowan at Melka Kunture (Ethiopia). In: Hovers E, Braun DR (eds) Interdisciplinary approaches to the Oldowan. Springer, Dordrecht, The Netherlands, pp 111–128

Plummer TW, Oliver JS, Finestone EM, Ditchfield PW, Bishop LC, Blumenthal SA,..., Potts R (2023) Expanded geographic distribution and dietary strategies of the earliest Oldowan hominins and Paranthropus. Sci 379(6632):561–566

Pobiner BL, Rogers MJ, Monahan C, Harris JW (2008) New evidence for hominin carcass processing strategies at 1.5 Ma, Koobi Fora, Kenya. J Hum Evol 55(1):103–130

Quallo MM, Price CJ, Ueno K, Asamizuya T, Cheng K, Lemon RN, Iriki A (2009) Gray and white matter changes associated with tool-use learning in macaque monkeys. PNAS USA 106(43):18379–18384

Raynal JP, Alaoui FZS, Magoga L, Mohib A, Zouak M (2004) The Lower Palaeolithic sequence of Atlantic Morocco revisited after recent excavations at Casablanca. Bulletin D'archéologie Marocaine 20:44–76

Rein R, Bril B, Nonaka T (2013) Coordination strategies used in stone knapping. Am J Phy Anthropol 150(4):539–550

Robinson JT, Mason RJ (1962) Australopithecines and artefacts at Sterkfontein. S Afr Archaeol Bull 17(66):87–126

Roussel M, Bourguignon L, Soressi M (2011) In: Morgado-Rodríguez A, Baena-Preysler J, Garcia-Gonzalez D, (eds) La investigacion experimental aplicada a la arqueología. Granada: Universidad de Granada

Sadek-Kooros H (1972) Primitive bone fracturing: a method of research. Am Antiq 37(3):369–382

Sahnouni M, Schick K, Toth N (1997) An experimental investigation into the nature of faceted limestone "spheroids" in the Early Palaeolithic. J Arch Sci 24(8):701–713

Sahnouni M, Hadjouis D, Van Der Made J, Canals A, Medig M, Belahrech H et al (2002) Further research at the Oldowan site of Ain Hanech North-Eastern Algeria. J Hum Evol 43(6):925–937

Sahnouni M, Parés JM, Duval M, Cáceres I, Harichane Z, Van der Made J et al (2018) 1.9-million-and 2.4-million-year-old artifacts and stone tool–cutmarked bones from Ain Boucherit, Algeria. Sci 362(6420):1297–1301

Salali GD, Chaudhary N, Bouer J, Thompson J, Vinicius L, Migliano AB (2019) Development of social learning and play in BaYaka hunter-gatherers of Congo. Sci Rep 9(1):11080

Schick KD, Toth N (1994) Early Stone Age technology in Africa: a review and case study into the nature and function of spheroids and subspheroids. In: Integrative Paths to the Past: Paleoanthropological Advances in Honor of F. Clark Howell. New Jersey: Prentice Hall

Sharon G, Feibel C, Alperson-Afil N, Harlavan Y, Feraud G, Ashkenazi S, Rabinovich R (2010) New Evidence for the Northern Dead Sea Rift Acheulian. PaleoAnthrop 2010:79–99

Shelley PH (1990) Variation in lithic assemblages: an experiment. J Field Archaeol 17(2):187–193

Shemer M, Crouvi O, Shaar R, Ebert Y, Matmon A, Horwitz LK et al (2019) Geochronology, paleogeography, and archaeology of the Acheulian locality of 'Evron Landfill in the western Galilee Israel. Quat Res 91(2):729–750

Shipton C (2010) Imitation and shared intentionality in the Acheulean Camb. Archaeol J 20(2):197–210

Sonoda K (2016) Constructing social learning in interaction among the Baka Hunter-Gatherers. In Terashima H, Hewlett B (eds.), Social learning and innovation in contemporary hunter-gatherers. Replacement of Neanderthals by modern humans series. Springer

Sternke F, Sørensen M (2009) The identification of children's flintknapping products in Mesolithic Scandinavia. In Mccartan SB, Schulting G, Warren G, Woodman P (eds.), Mesolithic horizons: Papers presented at the seventh international conference on the mesolithic in Europe, Belfast 2005. Oxbow Books, p 722–729

Stiner MC, Barkai R, Gopher A (2009) Cooperative hunting and meat sharing 400–200 kya at Qesem Cave Israel. PNAS 106(32):13207–13212

Stiner MC, Gopher A, Barkai R (2011) Hearth-side socioeconomics, hunting and paleoecology during the late Lower Paleolithic at Qesem Cave Israel. J Hum Evol 60(2):213–233

Stout D (2005) The social and cultural context of stone-knapping skill acquisition. In: Roux V, Bril B (eds.) Stone knapping: The necessary conditions for a uniquely hominin behavior. MacDonald Institute for Archaeological Research, p 331–340

Takakura J, Naoe Y (2019) The apprentice core: Evidence from a lithic refitting at the upper palaeolithic site Kyushirataki-5 in Hokkaido, Northern Japan. In: Nishiaki Y, Jöris O (eds) Learning among Neanderthals and palaeolithic modern humans. Springer, Replacement of Neanderthals by modern humans series, pp 119–127

Texier PJ, Roche H (1995) Polyèdre, sub-sphéroïde, sphéroïde et bola: des segments plus ou moins longs d'une même chaîne opératoire. Cahier Noir 7(31):e40

Titton S, Barsky D, Bargalló A, Serrano-Ramos A, Vergès JM, Toro-Moyano I et al (2020) Subspheroids in the lithic assemblage of Barranco León (Spain): Recognizing the late Oldowan in Europe. PLoS ONE 15(1):e0228290

Torres C, Preysler JB (2020) Experts also fail: A new methodological approach to skills analysis in lithic industries. J Paleolit Archaeol 3(4):889–917. https://doi.org/10.1007/s41982-020-00063-4

Torres Navas C (2022) Aprendizaje durante el Achelense y el Musteriense: estudio tecnoexperimental de los contextos de captación del centro peninsular (yacimientos de Los Ahijones. Universidad Autónoma de Madrid, Los Berrocales y El Cañaveral)

van Gijn A (1990) *The wear and tear of flint. Principles of functional analysis applied to Dutch neolithic assemblages*. Analecta Praehistorica Leidensia 22. Leiden University. Retrieved from https://hdl.handle.net/1887/15186

Villa P, Mahieu E (1991) Breakage patterns of human long bones. J Hum Evol 21:27–48

Willis LM, Boehm AR (2015) Evaluating the role of skill level in fish butchery. J Taph 13(1):1–15

Willoughby PR (1985) Spheroids and battered stones in the African Early Stone Age. World Archaeol 17(1):44–60

Winton V (2004) A study of Palaeolithic artefacts from selected sites on deposits mapped as clay-with-flints of southern England: With particular reference to Handaxe manufacture. Archaeopress, p 89–113

Wynn T, Overmann KA, Malafouris L (2021) 4E cognition in the lower palaeolithic. Adapt Behav 29(2):99–106

Yang SX, Huang WW, Hou YM, Yuan BY (2014) Is the Dingcun lithic assembly a "chopper-chopping tool industry", or "Late Acheulian"? Quat Inter 321:3–11

Yellen J (1977) Archaeological approaches to the present. Academic Press, New York, NY

Yustos PS, Diez-Martín F, Díaz IM, Duque J, Fraile C, Domínguez M (2015) Production and use of percussive stone tools in the Early Stone Age: experimental approach to the lithic record of Olduvai Gorge, Tanzania. J Arch Sc Rep 2:367–383

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