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How do stone knappers predict and control the outcome of flaking? Implications for understanding early stone tool technology

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ABSTRACT

The aim of the current study was to provide detailed data on the skill at controlling conchoidal fracture, data that may be used to help infer the processes responsible for generating the technological diversity observed in Early Stone Age sites. We conducted an experiment with modern stone knappers with different skill levels and systematically analyzed not only the products of flaking (i.e., detached flakes) but also the intentions prior to flaking, as well as the actions taken to control the shape of a flake through direct hard-hammer percussion. Only modern stone knappers with extensive knapping experience proved capable of predicting and controlling the shape of a flake, which indicated the significant difficulty of controlling the shape of flakes. Evidence was found that knowing the consequence of a strike given to a core at hand requires the acute exploration of the properties of the core and hammerstone to comply with the higher-order relationship among potential platform variables, kinetic energy of the hammerstone at impact, and flake dimension that reflects the constraints of conchoidal fracture. We argue that without this ability, controlling the shape of a flake or the organized *débitage* of flakes observed in some of the Early Stone Age sites may not have been possible. We further suggest that, given the difficulty and the nature of the skill, the evidence of precise control of conchoidal fracture in the Early Stone Age record may be indicative of the recurrence of a learning situation that allows the transmission of the skill, possibly through providing the opportunities for first-hand experience.

Introduction

A broad consensus among researchers holds that the emergence of intentionally modified stone tools marks a significant step toward the profound technological adaptation accomplished by the human species (e.g., Darwin, 1871; Leroi-Gourhan, 1964–1965/1993; Potts, 1991; Ambrose, 2001; Plummer, 2004). To date, the oldest reliably dated stone tools are 2.6 million years old (Semaw et al., 1997, 2003; Semaw, 2000). The world's earliest stone technologies are normally placed under the rubric of Oldowan (Leakey, 1971; Isaac, 1976) or Mode 1 (Clark, 1970) industries characterized by the production of sharp-edged flakes from cores. Oldowan industries have been contrasted with the subsequent Acheulean (or Mode 2) industries that emerged around 1.7–1.5 Ma, characterized by the elements of specific, standardized, and seemingly preconceived designs (Isaac and Curtis, 1974; Asfaw et al., 1992). The term Oldowan has also been used for early sites in Europe, such as Atapuerca (Carbonell et al., 1995, 1999, 2008; Bermudez de Castro et al., 1997; Parés et al., 2006) and Orce (Oms et al., 2000a,b), and in Asia, for instance at Riwat (Raynolds and Johnson, 1985; Rendell et al., 1989) and Longgupo (Huang et al., 1995), although different time scales are involved and different raw materials were used (Barskey, 2009).

Recent research has underscored the variability observed in Oldowan lithic assemblages in terms of reduction sequences, raw material procurement patterns, and perceived degree of technological competency (Roche et al., 1999; Plummer, 2004; Delagnes and Roche, 2005; Barskey, 2009; Braun and Hovers, 2009; Carbonell and Sala, 2009; Harmand, 2009). This has led some to posit a linear progression of technological developments, leading gradually to higher levels of technological complexity within the Oldowan (Barskey, 2009; Carbonell and Sala, 2009). Others suggest a technological stasis in which the same stone-working techniques and styles of tool manufacture persisted over 1 million years, arguing that the observed variability can be explained by variations in resource availability (Ludwig and Harris, 1998; Semaw et al., 1997, 2003; Semaw, 2000). Roche and her colleagues find neither the notion of linear technological evolution nor a long lasting static

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Oldowan acceptable (Roche et al., 1999; Delagnes and Roche, 2005; Harmand, 2009). These researchers noted that hominins from 2.34 Ma Lokalalei 2C site at West Turkana (Kenya) had distinct technical competencies marked by an organized core reduction sequence following constant technical rules far more sophisticated than those observed in other late Pliocene East-African sites, including the contemporaneous site of Lokalalei 1 which is located within walking distance of 2C (Roche et al., 1999; Delagnes and Roche, 2005; Harmand, 2009). Their discovery cast doubt on the theory of a linear evolutionary trend in lithic production, suggesting instead nonsynchronous evolutionary processes among early hominin groups (Roche et al., 1999; Delagnes and Roche, 2005). Similar arguments were made by de la Torre et al. (2003) who, in the analysis of 1.6–1.4 Ma Oldowan lithic assemblages from Peninj, discovered a hierarchical exploitation of the core surfaces, comparable to the Levallois method which is assumed to have appeared much later in time.

Many of the arguments circling around the current discussions of technological evolution in the Early Stone Age are based on the assessment of assemblage sophistication (Plummer, 2004). However, it is not an easy challenge to set a comparative framework embracing the variation observed among different sites (Plummer, 2004; Barskey, 2009). The variations in lithic assemblages reflect not only the technical competency of tool makers but also the available resources and their proximity, duration of occupation, functional needs, and other embedded contexts (Schick and Toth, 2006; Whiten et al., 2009). Obviously, since it is impossible to observe the evolving technological behaviors of hominin species directly, we can only see products rather than the process and underlying living behavior that created the prehistoric record (Stout, 2002; Whiten et al., 2009). As a consequence, isolating the factor that indicates the technical competency of stone tool makers in the Early Stone Age is beset with difficulties (Gowlett, 2009).

Yet, the technological diversity is not without limit, but is constrained by unifying invariants of the task of stone tool production (Pelegrin, 2005; Roche, 2005). It is generally agreed that the emphasis of Oldowan tool-making is on obtaining sharp cutting edges through flaking (Toth, 1985b; Pelegrin, 1993, 2005; Wynn, 2002; Roche, 2005). Sharp edges were produced by the specific fracture mechanism called conchoidal fracture (Pelegrin, 2005; Roche, 2005). The oldest stone tools found in the 2.6 Ma site at Gona are products of flaking that bear conspicuous bulbs of percussion—an unmistakable sign of conchoidal fracture (Semaw et al., 1997; Semaw, 2000). The production of sharp-edged flakes is inextricably bound to fracture mechanics (Pelegrin, 2005; Roche, 2005), and the act of flaking is always embedded and performed in the environment with certain supports and hindrances. Like us, prehistoric hominins were subject to physical forces, and the act of flaking took place in the same physical world, taking advantage of the principle of conchoidal fracture. Although the specific embedded context may vary, the unifying goal of producing flakes by means of conchoidal fracture leads to general convergence on the requirements of the task. As such, the degree of control over unifying requirements of conchoidal fracture may provide general insight into the technical competency and underlying behavior of the Plio-Pleistocene hominins responsible for making early stone assemblages.

Technological studies of stone knapping, however, whether based on archaeological materials (e.g., Sullivan and Rozen, 1985; de la Torre et al., 2003; Delagnes and Roche, 2005) or replicative knapping experiments (e.g., Bordes and Crabtree, 1969; Toth, 1985a; Braun et al., 2008), have focused on core reduction sequences. While it is undeniable that core reduction sequences represent a significant aspect of lithic technological variability, the attention paid to them has resulted in a shift away from even more fundamental processes of flaking by means of conchoidal fracture (Dibble, 1997). It should be emphasized that if the consequence of each flake removal were unpredictable and out of control, it would be impossible to carry out a core reduction sequence following a certain set of rules. Texier (1995: 652), addressing this point, wrote, "if the knapper is able to organize a *débitage*… he has already a good skill and knows exactly the consequences of a strike given to such a core."

At present, data about the skill of controlling conchoidal fracture are sparse. However, those that exist provide important insight. Results from field experiment on bead knapping in India (Roux et al., 1995; Bril et al., 2000, 2005; Roux and David, 2005), which follows the same mechanical principle of conchoidal fracture as stone knapping, suggested that the fine-tuning of the elementary percussive action is the most fundamental and difficult aspect of skill learning. Roux et al. (1995: 81) hypothesized that the most important part of learning consists of generating "the right forces to detach an adequate flake depending on the particular sub-goal at hand, which itself depends on the local configuration of the piece." Based on this hypothesis, Bril et al. (2010) investigated the ability of modern stone knappers to control the kinetic energy of the hammerstone at impact and found that experts were indeed adept at controlling kinetic energy, which was demonstrated by their ability to adjust striking movement according to changes in hammerstone weight in a manner that leaves the kinetic energy of the hammerstone at impact unchanged. Stout (2002) found that experts of adze-making in Iriyan Jaya were able to produce elongated flakes by exploiting steeper platform angles. He hypothesized that the difficulty of the task lies in the combination of increased knapping force with preserved striking accuracy, referring to Fitts' (1954) law.

These studies seem to converge toward an idea that skilled knappers can be distinguished by their ability to remove an appropriately shaped flake (Roux et al., 1995; Stout, 2002). However, what is required to control the shape of a flake has not been the subject of systematic inquiry and still remains poorly understood. No research has even tested to what extent modern stone knappers can predict the consequence of a strike given to a core, much less what is required to control the shape of a flake. With respect to the intention of a knapper, neither striking accuracy nor the adjustment of kinetic energy at impact has been quantified. And we still do not know how appropriate kinetic energy that varies according to the situation can be known to a knapper, and how kinetic energy affects the consequence of flaking.

Building on the previous studies on flaking skill, we investigated what is required to know and control the shape of a flake produced by conchoidal fracture. The aim of the current study was to provide detailed data on the skill of controlling conchoidal fracture, data that can be used to help infer the processes responsible for generating the technological diversity observed in Early Stone Age sites. Specifically, we conducted the experiment with modern knappers of different skill levels and systematically analyzed not only the products of flaking but also the intentions prior to flaking, as well as the regulation of action in controlling the shape of a flake by means of conchoidal fracture.

Conchoidal fracture

Conchoidal fracture refers to the phenomenon producing a Herzian cone, which leaves conspicuous bulbs of percussion on the fracture plane and razor-sharp cutting edges (Speth, 1972; Pelegrin, 2005; Roche, 2005). Types of stone that fracture conchoidally have a homogenous crypto-crystalline (e.g., flint, fine silicified sand-stone) structure or are glasses (e.g., obsidian) with no preferred planes of weakness. Although the exact physical principle of conchoidal fracture is not yet fully understood (Pelegrin, 2005), there have been a number of fracture experiments designed not to focus on the mechanics of conchoidal fracture itself but to document the relationships between particular variables and the shape of the flake (Speth, 1974, 1975; Dibble and Pelcin, 1995; Dibble, 1997; Pelcin, 1997a,b,c, 1998; Davis and Shea, 1998; Shott et al., 2000; Dibble and Rezek, 2009). These experiments often aim to estimate the properties of original tools from the variables retained in discarded tools. Most of these experiments were strictly controlled, using a protocol in which steel balls are dropped on plate glass.

These controlled experiments demonstrated that two aspects of the striking platform—platform size (i.e., platform depth, platform area) and exterior platform angle (see Table 1 for definitions)—have significant effects on flake size (i.e., flake weight, length, and area). For a given platform size, larger exterior platform angle will result in larger flakes, and for a given exterior platform angle, larger platform size will result in larger flakes (Speth, 1981; Dibble and Whittaker, 1981; Dibble and Pelcin, 1995; Dibble and Rezek, 2009). Dibble and Pelcin (1995) also demonstrated that, contrary to the conventional belief, neither momentum (product of weight and velocity) nor its individual components of weight and velocity has a major influence on flake size. Momentum does, however, play a critical role in determining whether or not a fracture can be initiated in the first place. Put differently, momentum is a threshold variable. A given momentum has the *potential* to detach a flake of a certain size. When the exterior platform angle and platform size combines to determine a flake size greater than the potential for that force, then no flake is produced. But once the threshold is reached, applying greater force will not result in larger flakes.

In summary, in the formation of flakes through conchoidal fracture there is a predictable relationship between flake dimension, platform dimension, exterior platform angle, and necessary percussive force required to initiate the fracture. These are by no means the only variables that affect the outcome, as conchoidal fracture proves to be susceptible to a large number of variables (Cotterell and Kamminga, 1987; Pelegrin, 1993). However, importantly, these variables are all under the direct control of the knapper and presumably are intentionally varied to achieve particular results (Dibble, 1997). Do knappers, prior to the detachment of a flake, attend to such relationship so as to control the consequence of a strike given to a core? We hypothesized that skilled knappers would know what to look for and predict the outcome of an action by complying with the higher-order relationships among these control variables.

Table 1
Flake terminology (see Fig. 1).

Flake	Any fragment detached from a raw material
Core	Any object from which a flake or a series of flakes is detached
Hammerstone	A stone that applies a force to a core
Striking platform	The fracture initiation surface on which a knapper strikes with a hammerstone
Flaking surface	The exterior face of the core which forms the exterior edge with striking platform
Flake length	The distance between the point of percussion and the most distal point along the central axis of the flake
Flake width	The distance between two lateral edges of a flake at the midpoint of the length measurement
Flake area	Approximated as the product of flake length and flake width
Platform depth	Distance between the point of percussion to the exterior edge along the platform surface
Platform width	The widest point of the platform at the exterior surface of the core
Platform area	Approximated as the product of platform depth and platform width
Exterior platform angle	The angle between striking platform and exterior surface which is formed by two lines—one represented by the platform depth, the other extending down the exterior face directly in line with the axis of percussion to a distance equal to the platform depth (Dibble, 1997)

Experiment

In the experiment, knappers were instructed to control the shape of a flake produced by conchoidal fracture. Knappers were first instructed to draw on the core the outline of a flake they intend to detach with a marker, and then to detach the flake as predicted through direct percussion with a hammerstone. This method allowed for the analysis not only of the products of flaking but also of the intention of the knapper prior to the act of flaking by measuring the attributes of predicted vs. realized (detached) flakes (Figs. 1 and 2). In addition, we recorded the movement of the striking hand of the knapper using a three-dimensional motion capture system. By matching the data of predicted outlines, detached flakes, and striking movement, we systematically investigated how knappers control the consequence of a strike given to a core at hand, as well as to what extent they can control the shape of a flake produced by conchoidal fracture.

Participants

Twenty-two volunteer participants (five women and seventeen men) were grouped into three categories: five experts, six intermediates, and eleven novices. Knappers with more than twenty years of active knapping experience were grouped as experts. Knappers with several years of active knapping experience were grouped as intermediates. Novices included those with or without

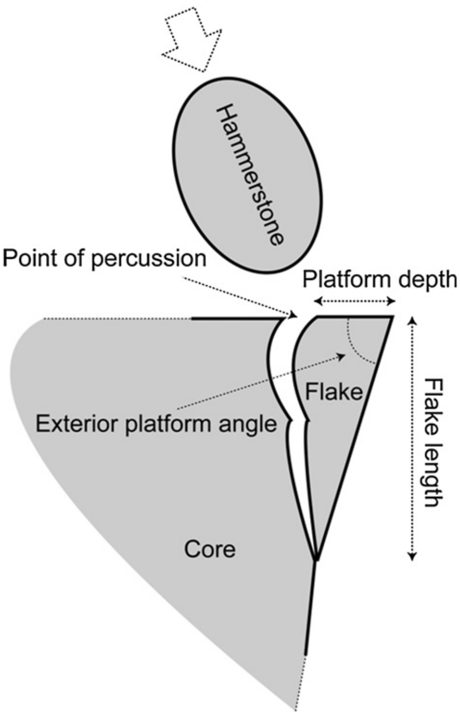

Figure 1. Flake terminology.

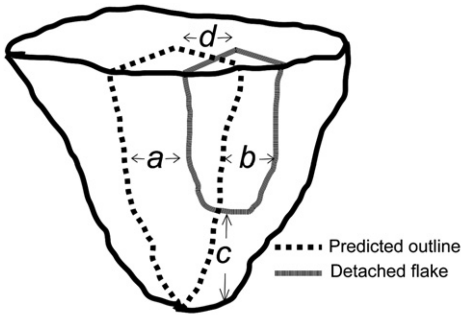

Figure 2. The measurements made on predicted and detached flakes (*a*+*b*: difference in lateral axis, *c*: difference in length, *d*: distance between points of percussion between predicted and detached flakes).

brief knapping experience. Some participants had a moderate amount of experience but a long time ago, and these were categorized as intermediate or novice based on their demonstrated skill. This assignment to one group or the other was done by an expert knapper prior to the experiment to avoid any bias from the experimental results. Novices without prior experience were trained during one 2-h session preceding the experiment comprising a combination of instructions, demonstration, and practical experience. Participants gave informed consent prior to participation and were not compensated for participation. Thirteen participants were from the Department of Archaeology of Southampton University, three experts were British professional knappers, and six participants were from the UMR 7055–CNRS-University of Nanterre in Paris. Mean age of the participants was 39 ± 11 years, mean height was 175 ± 7 cm, and mean weight was 75 ± 10 kg.

Apparatus

Flint cores were used in the experiment. Flint is a fine-grained form of chert which has the natural property of conchoidal fracture, and was used in Mode 1 assemblages in Europe, for instance at Atapuerca (Parés et al., 2006). Prior to the experiment, raw flint nodules were roughly pre-shaped by an expert knapper into a frustum shape (truncated pyramid, see Fig. 2) in order to standardize the cores used by each participant. Even after this pre-shaping, however, the core shapes were still quite irregular due to the nature of the raw material. The hammerstone used was individually chosen by each participant from those with a range of different weight. A Kruskal–Wallis test of differences found no significant difference between groups in both the weight of selected hammers and that of flint cores used.

Opaque, water based acrylic paint markers were used for marking outlines on the flint core. Participants were seated on a chair during the experiment. Movements of the striking arm were recorded using a magnetic tracking system (Polhemus Liberty, Polhemus Corporation, Colchester, VT) at 240 Hz. Sensors were attached with tape to the dorsal side of the hand and forearm, the lateral surface of the humerus, and to the acromion following the procedure used by Biryukova et al. (2000), although only the data from the marker on the hand were used for analysis in the current experiment.

Procedure

The task for the participant in each trial was to control the shape of a flake. Each participant made three predictions followed by three actual flake removals. Participants first marked on the flint core the outline of the flake to be detached with a paint marker the color of which corresponded to the trial number. The knappers then detached a flake by direct percussion using the self-selected hammerstone. If a strike did not detach a flake, participants were allowed to perform up to two more strikes until a flake was detached. All the data including non-successful strikes were used in the analysis of striking movement and prediction, although the data of unsuccessful trials were naturally excluded from the analysis of detached flakes.

Table 2
Dependent variables in the experiment

Variables (unit)	Abbreviation	Measurement
Predicted outlines		
Predicted length (mm)	(L_p)	From the midpoint of the outline on the platform to the most distal point of the outline along the central axis of the predicted flake.
Predicted width (mm)	(W_p)	At the midpoint of the length measurement, perpendicular to length.
Predicted area (cm^2)	(A_p)	Dorsal surface area of the predicted flake, approximated as the product of predicted flake length and predicted flake width.
Predicted platform depth (mm)	(PD_p)	The distance from the outline to the exterior edge along the predicted platform surface.
Predicted platform width (mm)	(PW_p)	At the exterior surface of the core, widest point of the outline on the predicted platform.
Predicted platform area (cm^2)	(PA_p)	Outlined platform surface area, approximated as the product of platform depth and platform width of the predicted outline.
Selected exterior platform angle (°)	(EPA_p)	The angle between the predicted platform surface and exterior surface (see Table 1 and Fig. 1 for the details).
Detached flakes		
Flake length (mm)	(L_f)	From the point of percussion to the most distal point along the central axis of the flake.
Flake width (mm)	(W_f)	At the midpoint of the length measurement, perpendicular to flake length.
Flake area (cm^2)	(A_f)	Dorsal flake surface area, approximated as the product of flake length and flake width.
Discrepancy between prediction and outcome		
Difference in length (mm)	(ΔLe)	Flake length subtracted by predicted length in absolute value (*c* in Fig. 2).
Difference in lateral axis (mm)	(ΔLa)	Sum of distances between predicted outline and detached flake at lateral edges on both sides at the midpoint of the length axis (*a*+*b* in Fig. 2).
Sum of differences (mm)	(ΔS)	Sum of differences in length and lateral axis (*a*+*b*+*c* in Fig. 2).
Accuracy of the Strike (mm)	(ΔP)	Distance from percussion point to the midpoint of outline on the platform relative to the two lateral edges (*d* in Fig. 2).
Striking action		
Kinetic energy (J)	(E_k)	$E_k = ½mv^2$, where v is resultant velocity at impact and m is the weight of the hammer plus the approximate weight of the hand.
Trajectory Length (cm)	(T)	The trajectory length of the hand sensor in 3D space during striking movement from the highest vertical point to the percussion point.

Table 3
Means, standard deviations, and coefficients of variation of attributes of predicted flakes

	L_p(mm)			W_p(mm)			PD_p(mm)			PW_p(mm)			EPA_p(°)		
	M	SD	CV	*M*	SD	CV	*M*	SD	CV	*M*	SD	CV	*M*	SD	CV
Experts	82.6	24.4	0.30	40.8	9.6	0.24	13.6	2.9	0.22	43.2	8.4	0.19	68.1	10.4	0.15
Intermediate	63.3	13.8	0.22	32.4	7.1	0.22	14.9	3.5	0.24	41.1	9.6	0.23	59.1	6.9	0.12
Novice	44.1	12.3	0.28	32.2	11.6	0.36	13.5	4.0	0.29	47.2	12.9	0.27	59.1	9.8	0.17

Data analysis

The dimension of predicted outlines on the cores as well as that of detached flakes were measured in the manner that is comparable to published flake analyses (Speth, 1975; Dibble and Pelcin, 1995; Dibble, 1997; Pelcin, 1997a,b,c, 1998; Davis and Shea, 1998; Shott et al., 2000). The attributes chosen for examination were those which are measurable in both predicted outline and detached flakes: flake length, flake width, flake surface area, platform depth, platform width, platform area, and exterior platform angle (see Fig. 1 and Table 2 for definitions). The discrepancy between predicted outlines and detached flakes was described in terms of the distance between outlines in lateral axis at the midpoint of the flake length ($a+b$ in Fig. 2), the difference in flake length (c in Fig. 2), and the sum of these measures ($a+b+c$ in Fig. 2). The morphology of the selected flaking surface of the core was assessed by two raters, the first author (rater 1) and a doctoral student in prehistory from *Universitat Rovira i Virgili* who volunteered for the analysis (rater 2), whether the profile of the dorsal surface of the predicted flake was convex/flat or concave. In addition, as three flakes were removed by each participant, whether subsequent removals (i.e., the second and the third flakes) were made in areas impacted by previous removals was indicated. Two variables from the movement data were calculated for each strike: (a) kinetic energy of the hammer plus hand at impact, and (b) trajectory length of the striking hand from the highest vertical point in the striking movement to the percussion point, following the procedure in Bril et al. (2008, 2010). The point at the instant of the blow and the point of maximum hand height were determined by visual inspection of the data. Kinetic energy was calculated using the formula $E_k = ½mv^2$ (v = resultant velocity) based on the weight of the hammer plus the approximate weight of the hand according to the anthropometrical tables provided by Zatsiorsky (2002), and the velocity of the hand marker at impact was calculated using a three-point finite difference algorithm. The trajectory length of the striking hand was calculated based on the spatial trajectory of the hand sensor in 3D space. The accuracy of the striking point was described in terms of the distance from the actual point of percussion, a visible mark on the core and flake left by hammer percussion, to the predicted point of percussion, approximated as the midpoint of the predicted outline drawn on the platform (d in Fig. 2). The marker used was about 4 mm thick. For the sake of consistency, we defined the distance between predicted and actual impact points as zero if the impact point was within this 4 mm square of the marked point. If the impact point fell outside of the line, the distance was measured from the closest edge of the line. Following Dibble (1997), a very conservative approach was taken with regard to all of these measurements: if landmarks were unclear, or if it looked as though a portion were missing, then the measurement was recorded as missing.

All measurements were calculated for each individual strike for all participants. A simple linear regression analysis was used to test the correlation among selected variables. A linear mixed-model analysis was used to test the effect of skill level on the means of each selected variable. To account for the correlation between strikes made by the same participant, a subject factor was included as an additional random-effect (Boyle and Willms, 2001). In the analysis of movement variables, flaking success was also included as a fixed effect in the linear mixed model because we included the data from unsuccessful strikes in addition to successful strikes. Bonferroni-adjusted pairwise comparisons based on estimated marginal means were used for multiple comparisons between skill levels. All statistical tests were made using SPSS 16.0. The alpha value for a significant effect was set at 0.05.

Results

Sample videos of the experiments can be found in the supplementary online material (SOM) for this paper (doi:10.1016.j.jhevol.2010.04.006).

Success rate of flaking

Of 104 strikes, 61 strikes were successful in detaching flakes. Success rates of flaking were 73% for experts, 61% for intermediates, and 54% for novices.

Dimension of predicted flakes

The mean lengths of the predicted flakes marked on the cores were 82.6 mm, 63.3 mm, and 44.1 mm, and the mean widths were 40.8 mm, 32.4 mm, and 32.2 mm for experts, intermediates, and novices, respectively (Table 3). Pearson's correlation analysis did not find significant correlation between the weight of cores used and the length or width of predicted flakes in any of the three skill level groups ($p > 0.5$). There was a significant main effect of skill level on mean predicted flake length, $F(2,19) = 18.51$, $p < 0.001$, and the differences were significant between each pair of the three skill level groups ($p < 0.05$). On the other hand, there was no significant effect of skill level on mean predicted flake width. Experienced knappers, on average, found the possibility of detaching longer but not wider flakes in cores compared to less experienced knappers.

Dimension of detached flakes

The mean lengths of the actual flakes detached by strikes were 84.8 mm, 68.1 mm, and 42.6 mm, and the mean widths were 47.8 mm, 41.8 mm, and 37.2 mm for experts, intermediates, and novices, respectively (Table 4). Pearson's correlation analysis did not find significant correlation between the weight of cores used and the length or width of detached flakes in any of the three skill level groups. There was a significant main effect of skill level on

Table 4
Means, standard deviations, and coefficients of variation of attributes of detached flakes

	L_f (mm)			W_f (mm)		
	M	SD	CV	*M*	SD	CV
Experts	84.8	29.4	0.35	47.8	15.9	0.33
Intermediate	68.1	23.1	0.34	41.8	17.1	0.41
Novice	42.6	17.9	0.42	37.2	18.2	0.49

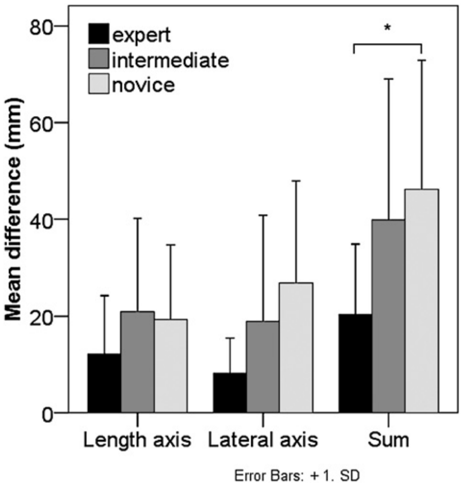

Figure 3. Mean differences between predicted and detached flakes.

mean flake length, F(2,19) = 17.41, $p < 0.001$, and the flakes detached by novices were significantly shorter than the other two skill level groups ($p < 0.01$). The effect of skill level on mean flake width was not significant.

Comparison between predicted and detached flakes

The above results show that the mean dimensions of predicted and detached flakes generally agreed in all skill level groups. However, this does not mean they all detached flakes as they predicted. For instance, you may predict a flake of 50 mm long and detach a flake of 100 mm in one trial, then predict a flake of 100 mm long and detach a flake of 50 mm in another trial. The mean values of these two trials are the same across prediction and outcome, but, in fact, the prediction and the outcome within each trial are different by 50 mm.

The difference in dimension between the predicted outline and the detached flake was measured for each trial, and the mean differences in dimension (not the difference between the mean values of dimension) were compared across skill levels (see Fig. 2 for the measurements taken). The mean absolute values of the differences between predicted outlines and detached flakes in length axis were 12.2 mm, 21.4 mm, and 19.3 mm, and those in lateral axis were 8.2 mm, 18.9 mm, and 25.8 mm for experts, intermediates, and novices, respectively. There was a significant main effect of skill level on the sum of the length and lateral differences ($a+b+c$ in Fig. 2), F(2,17) = 3.99, $p < 0.05$, which was significantly smaller for experts than novices ($p < 0.05$). However, the effect of skill level on the mean difference in either axis alone was not significant (Fig. 3).

The simple linear regression of predicted flake length (L_p) on detached flake length (L_f) was significant in the expert group, $L_f = 4.219 + 0.975 \times L_p$, $R^2 = 0.655$, $p < 0.001$, but not significant in the intermediate and novice groups (Fig. 4a). Similarly, the simple linear regression of predicted flake width (W_p) on detached flake width (W_f) was significant in the expert group, $W_f = -2.089 + 1.225 \times W_p$, $R^2 = 0.548$, $p < 0.01$, but not significant in the intermediate and novice groups (Fig. 4b).

Expert knappers were able to predict the shape of the flake to be detached, and the flakes were realized with considerable accuracy. Experts even took the risk of predicting elongated flakes, which are considerably more difficult to detach compared to shorter flakes (c.f., Bril et al., 2010).

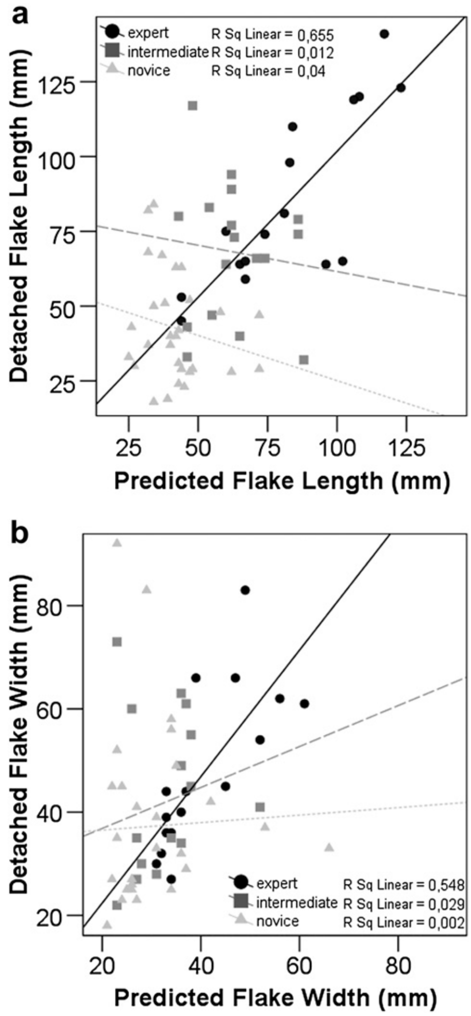

Figure 4. a) Detached flake length as a function of predicted flake length. b) Detached flake width as a function of predicted flake width.

Selection of the flaking surface

While experts always selected either a flat or convex face as a flaking surface, novices did not exhibit such selectivity (Table 5). Chi-squared tests found significant differences among skill level groups in the morphology of the selected flaking surface assessed by both raters (rater 1: $\chi^2 = 13.25$, df = 2, $p < 0.01$; rater 2: $\chi^2 = 15.04$, df = 2, $p < 0.01$). The classifications by the two raters were in substantial agreement ($\kappa = 0.741$, $p < 0.001$).

Thirty-six percent of the subsequent removals (i.e., the second and third flake removals) by experts were targeted on areas impacted by previous removals, while those of intermediates and novices were almost never targeted on the location of the core impacted by previous removals (Table 6). Chi-squared tests found a significant difference among skill level groups in the location of the core selected for subsequent removals ($\chi^2 = 9.27$, df = 2, $p < 0.05$).

Table 5
Morphology of the selected flaking surface

	Rater 1		Rater 2	
	Flat/convex (%)	Concave (%)	Flat/convex (%)	Concave (%)
Expert	100	0	100	0
Intermediate	72	28	61	39
Novice	48	52	42	58

Table 6
Areas of the core selected for the second and third flake removals

	Previously removed area (%)	Other area (%)
Expert	36	64
Intermediate	0	100
Novice	5	95

Platform variables of predicted flakes

The mean platform depths of predicted flakes were 13.6 mm, 14.9 mm, and 13.5 mm, the mean platform widths were 43.2 mm, 41.1 mm, and 47.2 mm, and the mean external platform angles were 68.1°, 59.1°, and 59.1° for experts, intermediates, and novices, respectively (Table 3). There was a significant main effect of skill level on mean exterior platform angle, $F(2,19) = 3.92$, $p < 0.05$, where the selected angle was almost significantly greater for experts compared to novices, $p = 0.05$. No main effect of skill level was found on the mean depth or width of predicted platforms.

Higher-order relations among platform variables and dimensions of predicted flakes

In the formation of flakes through conchoidal fracture, there is interdependence between flake size, platform size, and exterior platform angle (Dibble, 1997). We tested whether this relationship holds in the predictions made prior to the detachment of a flake. The simple linear regression of exterior platform angle (EPA_p) on the ratio of predicted flake length to predicted platform depth (L_p/PD_p) was significant only in the expert group, $L_p/PD_p = -6.145 + 0.184 \times EPA_p$, $R^2 = 0.696$, $p < 0.001$ (Fig. 5a). Likewise, the simple linear regression of exterior platform angle on the ratio of predicted flake area to predicted platform area (A_p/PA_p) was significant in the expert group, $A_p/PA_p = -10.437 + 0.248 \times EPA_p$, $R^2 = 0.597$, $p < 0.001$ (Fig. 5b), but not so in the other two groups. Only the predictions made by experts specified the mechanics of conchoidal fracture.

Simple linear regressions of exterior platform angle on both the length and area of predicted flakes were significant in the expert group, $L_p = -18.967 + 1.490 \times EPA_p$, $R^2 = 0.405$, $p < 0.01$, $A_p = -20.24 + 0.798 \times EPA_p$, $R^2 = 0.340$, $p < 0.05$, respectively. Yet, neither the simple linear regression of predicted platform depth on predicted flake length nor the regression of predicted platform area on predicted flake area was significant in the expert group. These results suggest that experts were selecting the striking platform with greater exterior platform angle when predicting larger flakes while maintaining the higher-order relationship between potential flake size, platform size, and exterior platform angle. The predictions made by the other two groups did not exhibit such regularity; in the novice group, however, the simple linear regression of predicted platform area on predicted flake area was significant, $R^2 = 0.465$, $A_p = 3.71 + 1.683 \times PA_p$, $p < 0.001$. Apparently, novices increased solely the area of the striking platform with the increase of predicted flake area, without attending to the higher-order relationship that reflects the constraints of conchoidal fracture.

Kinetic energy

The mean values of the kinetic energy of the hammerstone at impact for experts, intermediates, and novices were 4.5 J, 6.5 J, and 10.1 J, respectively (Table 7). Mixed-model analysis on mean kinetic energy found no significant main effects. However, the effect of skill level was nearly significant, $F(2,20) = 3.49$, $p = 0.051$, indicating a tendency of kinetic energy to be lower in experienced knappers compared to less experienced knappers.

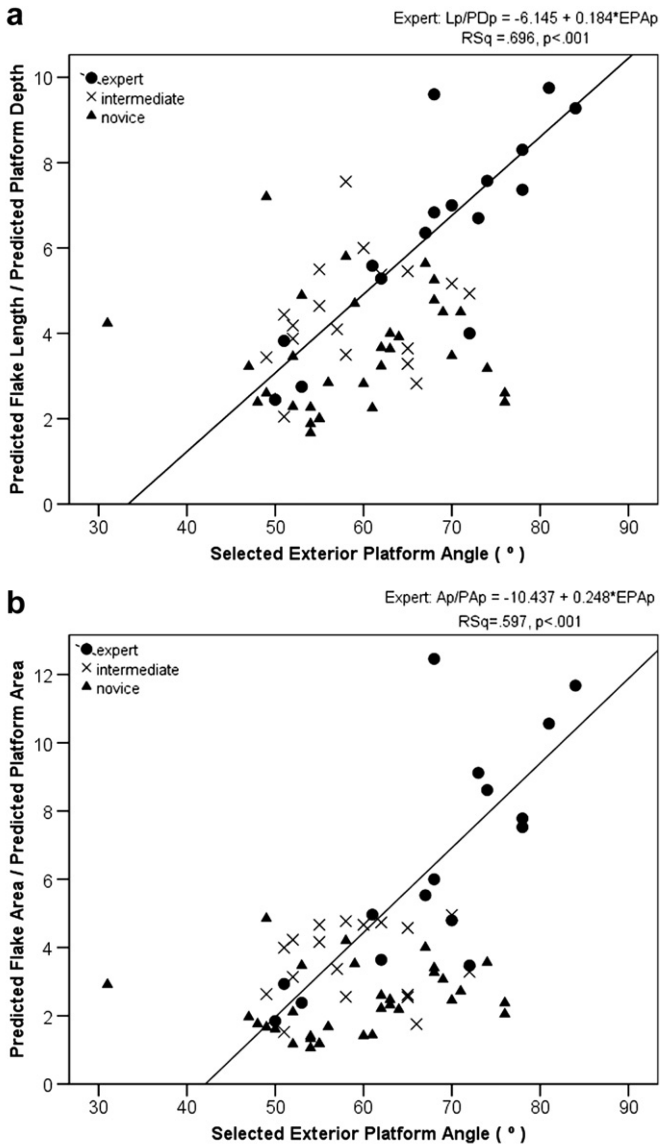

Figure 5. a) The ratio of predicted length to platform depth as function of exterior platform angle. b) The ratio of predicted area to platform area as a function of exterior platform angle.

Trajectory length

The mean trajectory lengths of the hammer in three-dimensional space for experts, intermediates, and novices were 14.4 cm, 22.1 cm, and 31.0 cm, respectively (Table 7). There was a significant main effect of skill level on mean trajectory length, $F(2,20) = 7.82$, $p < 0.01$, and the trajectory length of the hammerstone during striking movement was significantly shorter for experts compared to novices ($p < 0.01$).

Accuracy of the strike

The mean distances between predicted and actual striking points for experts, intermediates, and novices were 0.6 mm, 4.3 mm, and 7.4 mm, respectively (Fig. 6). There was a significant main effect for skill level, $F(2,19) = 6.74$, $p < 0.01$, and the strikes

Table 7
Means, standard deviations, and coefficients of variation of variables measured on striking action

	E_k			T (cm)		
	M	SD	CV	*M*	SD	CV
Experts	4.4	2.3	0.53	14.4	3.1	0.22
Intermediate	6.5	3.8	0.57	22.1	6.3	0.29
Novice	10.1	5.2	0.52	31.0	10.9	0.35

were significantly more accurate for experts compared to novices ($p < 0.05$).

Did kinetic energy reflect prediction?

The simple linear regressions of kinetic energy (E_k) on both the length and area of predicted flakes were significant: $L_p = 50.537 + 6.907 \times E_k$, $R^2 = 0.513$, $p < 0.01$, $A_p = 15.755 + 3.918 \times E_k$, $R^2 = 0.466$, $p < 0.001$, respectively (Fig. 7). The kinetic energy of the hammerstone at impact reflected the dimension of the to-be-detached flake only in the expert group.

How did kinetic energy influence detached flakes?

We found that the majority of the platforms of flakes detached by novices were ruined by percussion, often crushed into tiny splinters. The percentages of the flakes with platform crushing were 19%, 7%, and 61% for experts, intermediates, and novices, respectively. A logistic regression analysis revealed that kinetic energy was a significant predictor of platform crushing, $p < 0.01$, where for every 1 J increase in kinetic energy, the odds of platform crushing increased by a factor of 1.24. The contribution of unsuccessful strikes to platform shatter was not obvious. Out of 61 successful strikes that contributed to the analysis, 41 strikes were made without previous unsuccessful strikes, 15 strikes were made after one unsuccessful strike, and 5 strikes were made after two unsuccessful strikes. The percentages of flakes with platform crushing in each of above cases were 37.5%, 40%, and 20%, respectively.

In the expert group, a linear simple regression revealed that kinetic energy was a significant predictor of flake length ($L_f = 44.677 + 8.449 \times E_k$, $R^2 = 0.521$, $p < 0.01$) and also of flake area ($A_f = 19.744 + 4.56 \times E_k$, $R^2 = 0.310$, $p < 0.05$; Fig. 8). In the other two groups, no significant linear relationships were found between kinetic energy and flake dimensions.

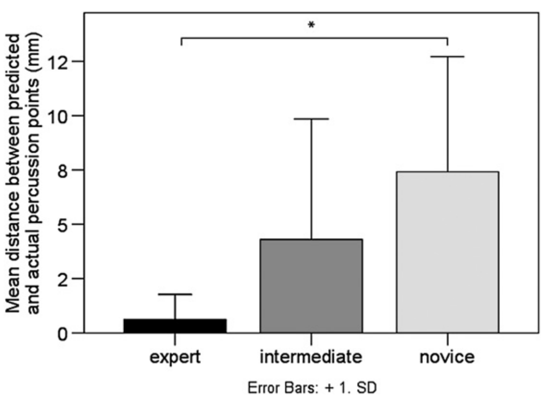

Figure 6. Striking accuracy for each skill level group.

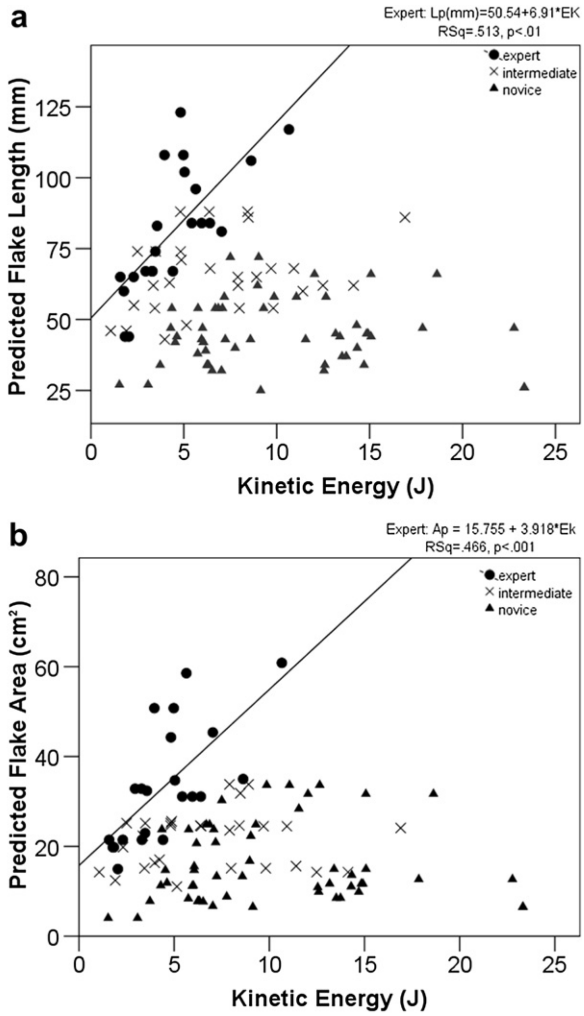

Figure 7. a) Predicted flake length as a function of kinetic energy. b) Predicted flake area as function of kinetic energy.

Discussion

The control of flaking by means of conchoidal fracture has been recognized by archaeologists as a fundamental aspect of the skill involved in stone knapping (Pelegrin, 1990, 1993, 2005; Roux et al., 1995; Roche et al., 1999; Steele, 1999; Bril et al., 2005; Delagnes and Roche, 2005; Roche, 2005). In the experiment involving modern knappers with different skill levels, we systematically analyzed not only the products of flaking (i.e., detached flakes) but also the intentions prior to flaking and the control of actions controlling the shape of a flake. The data allowed for an examination of the different aspects of controlled flaking, which arguably has several important implications that supplement the current knowledge of lithic technological skills in the Early Stone Age. Summarily, the results are as follows:

(i) Only experts were able to predict the shape of the product of flaking. The shape of a flake *predicted* by experts exhibited the relationship between platform variables and flake dimensions that reflects the constraints of conchoidal fracture.
(ii) Although knappers were not asked to maximize flake length but simply asked to control the shape of a flake, experts predicted and removed longer flakes than less-skilled knappers. As they predicted longer flakes, experts selected greater exterior platform angle while maintaining the invariant

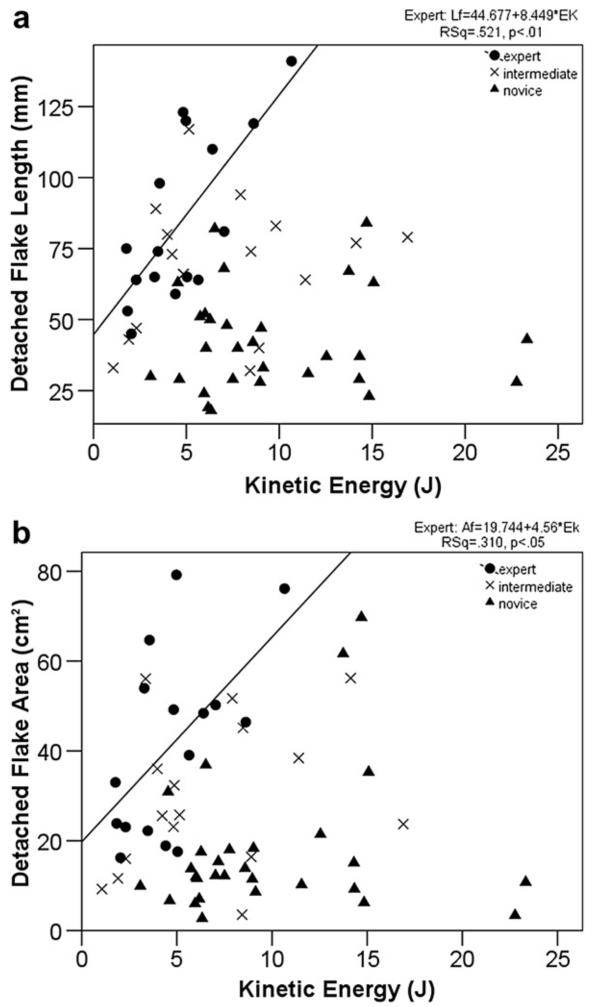

Figure 8. a) Detached flake length as a function of kinetic energy. b) Detached flake area as function of kinetic energy.

relationship between exterior platform angle and the ratio of predicted flake length to platform depth.

(iii) Experts always selected a flat or convex face of the core as a flaking surface, which sometimes included areas impacted by previous removals.

(iv) The kinetic energy of the hammerstone at impact reflected the dimensions of the predicted flake only in the expert group.

(v) The strikes of experts tended to accompany relatively lower kinetic energy of the hammerstone at impact with more accurate control of point of percussion compared to less-skilled knappers.

Implication for the evolutionary development of controlled flaking

The emphasis of early Oldowan tool-making is on obtaining sharp edges, and early Oldowan tools exhibit little or no attention to the shape of the flaked products (Toth, 1985b; Wynn, 2002). Yet, at the level of individual flake removals, as opposed to finished artifacts, recent findings show evidence that Oldowan knappers controlled flake shape to some extent so as to maintain or modify the morphology of the core surface in such a way as to provide further opportunities for subsequent flaking (Roche et al., 1999; de la Torre et al., 2003; Roche, 2005). Roche (2005) called such elaborated flaking activities “organized *débitage*” as opposed to simple flaking to obtain sharp edges. The organized *débitage* scheme necessarily requires a knapper to predict the consequence of a strike on a core (Texier, 1995). The result of our experiment revealed that it is difficult for a knapper to accurately predict the morphology of a flake. Only experts with extensive knapping experience were able to predict and control the shape of a flake removed from a core. Precisely controlling the path of conchoidal fracture seems to add a new level of complexity to the task of simply obtaining sharp-edged flaked products. We infer that the appearance of the organized *débitage* of flakes found in some Oldowan sites may have reflected the development of the ability to evaluate and control the consequence of each flaking, rather than the emergence of mental abstraction to organize a core reduction sequence as suggested by some researchers (e.g., de la Torre et al., 2003).

What, then, is required to know the consequence of a strike? As mentioned in the introduction, in the formation of flakes through conchoidal fracture there is a lawful relationship between flake dimension, platform dimension, exterior platform angle, and the kinetic energy at impact required to initiate the fracture. Because these variables are all under the direct control of the knapper, we hypothesized that knappers prospectively attend to the relationship among them to predict and control the consequence of flaking. Confirming the hypothesis, the result of the current experiment revealed that, prior to the removal of a flake, the outline of a flake predicted by experts already exhibited the higher-order relationship between platform variables and flake dimensions that reflects the constraints of conchoidal fracture. On the contrary, no such relationship appeared in the flakes predicted by the less-skilled knappers. In addition, while experts always selected a flat or convex face of the core as a flaking surface, novices did not show such selectivity but often intended to exploit the concave flaking surface that is not suitable for flake production (Delagnes and Roche, 2005). Differences were found between expert knappers and less-skilled knappers not only in the products of flaking but also in the intentions prior to the act of flaking. This result suggests that the major difficulty in controlling the shape of a flake lies in appreciating the morphological removal possibilities of a core at hand. Simply put, novices intended to detach rather impossible flakes, while experts intended to detach feasible flakes.

This result further provides clues to the question of how experts can establish feasible predictions. Experts predicted the shape of a flake by attending to the higher-order relationship between platform variables and flake dimensions, which could be adjusted by selecting different striking locations on the core. The fact that predictions made by experts specified the constraints of conchoidal fracture suggests that what is required to control the shape of a flake is the ability to discriminate the features of a core that affect the morphology of a flake.

Another interesting point is the fact that experts seemed not only capable of predicting and detaching the most obvious flake possible but of selecting a particular flake among the range of possibilities given by a core at hand. In our experiment, although knappers were not instructed to maximize the length of a flake, experts consistently predicted and realized elongated flakes. This implies the ability of expert knappers to select a certain fracture path from the range of possibilities offered by the properties of a core. In other words, expert knappers are not only capable of predicting a flake but also capable of predetermining a flake to some extent within the range of available possibilities. When removing longer flakes, experts selected steeper exterior platform angles while maintaining the invariant relationship between exterior platform angle and the ratio of predicted flake length to platform depth. This result is consistent with previous work by Stout (2002) who reported that the flakes produced by highly skilled knappers were longer and had steeper exterior platform angles compared to less-skilled knappers' flakes.

The evidence of a tendency toward elongated flakes and the acute perception of platform constraints were also found in the archaeological record. Delagnes and Roche (2005: 465–466) analyzed the lithic assemblage at Lokalalei 2C and wrote, "(a)s the flakes produced are proportionately long, and each one usually travels across at least half the flaked surface, they rapidly cover the entire surface.... In order to ensure the removal of more than a few relatively invasive flakes from an initially flat or slightly convex surface, this surface must be kept flat by the *débitage* process itself." At Lokalalei 2C, the removal of elongated flakes apparently played a role in keeping the flaking surface flat—which, in turn, provided opportunity for subsequent flaking. To do this, Lokalalei 2C knappers selected raw materials presenting an abundant portion of surfaces with directly serviceable exterior platform angles and delivered blows at the spot without trial and error (Delagnes and Roche, 2005; Harmand, 2009). It is evident that Lokalalei 2C knappers paid attention to the constraints of exterior platform angle that have a direct effect on flake morphology (Roche, 2005). Interestingly, however, at the closely-located, contemporaneous site of Lokalalei 1, globular cobbles were selected with little or no attention to the availability of naturally serviceable striking surfaces, and a number of unsuccessful blows were aimed at the portion showing no proper exterior platform angles (Delagnes and Roche, 2005; Harmand, 2009). Harmand (2009) holds that these differences are related to the degree of selectivity for raw material morphologies as well as to the way they were processed, rather than to variations in resource availability. In the current experiment, we found that experts removed longer flakes, and that subsequent removals by experts, unlike the other groups, were sometimes made in areas impacted by previous removals. Although the current experimental condition is not an exact analog for Lokalalei assemblages, certain commonalities appeared between the results of the current experiment and the characteristics of the assemblages in Lokalalei sites, in that one group of knappers was more capable of detecting the core features that influence flaking than the other groups.

The results of the current experiment further demonstrated that this ability to detect the constraints and opportunities for achieving the task provides the foundation for the control of the action. Experts in this experiment tended to hit the core with lower kinetic energy of the hammerstone than did less-skilled knappers, replicating the results of Bril et al. (2010). But our result is all the more striking because experts in this experiment predicted and detached consistently longer flakes than did the other skill level groups. It is known that the increase of percussive force above the threshold of flake initiation has little effect on flake size (Dibble and Pelcin, 1995). The fact that there was no correlation between flake size and kinetic energy in the intermediate and novice groups suggests that less-skilled knappers were overshooting the threshold of kinetic energy required to initiate the fracture. On the other hand, the tendency for the use of lower kinetic energy (and its linear relation to the dimension of detached flakes) by the experts implies that the kinetic energy of the strikes of experts was close to the threshold, which is determined by the size of potential flake, which in turn is determined by the combination of exterior platform angle and platform size if the core is homogeneous (Dibble and Pelcin, 1995). Furthermore, the fact that kinetic energy was specific to the predicted flake size in experts suggests that experts were tuning their action into yet another higher-order functional relationship among platform variables, intended flake size, and the required kinetic energy determined by these platform variables. Contrary to novices who tended to strike a core with great force, experts, although tacitly, seemed to know the properties of a core at hand and detached flakes with accurate movements without overshooting the required kinetic energy by too much. This implies that the challenge may lie not in the control of kinetic energy of the hammerstone at impact *per se*, but in the detection of the threshold of kinetic energy required to initiate the fracture.

The same is true for controlling striking accuracy. In direct hard-hammer percussion, the point of contact is usually blocked from view (Pelegrin, 1993). Controlling the point of percussion requires feeling how far the tip of a hammerstone extends from the hand, the orientation of the hammerstone, and how the hammerstone should be brought into contact with the striking platform (Wagman and Taylor, 2004). People are capable of perceiving geometric properties of hand-held objects by wielding them, as the rotational inertias of the wielded object dynamically affects the patterning of activity in the ensembles of muscle and tendon receptors (Gibson, 1966; Turvey and Carello, 1995; Turvey, 1996). The striking accuracy of experts implies that they were more finely attuned to such perceptual information compared to less experienced knappers. This further suggests that accuracy of the strike does not depend on the control of bodily movement or on the biomechanical capability *per se*, but on the ability of a knapper to feel the tip of the hammerstone in relation to the hand and the core (Wagman, 2002).

In summary, modern stone knappers with extensive knapping experience proved capable of predicting and controlling the shape of a flake by detecting the features of the environment that influence flaking. What characterizes the degree of control over conchoidal fracture? What is required to control the shape of a flake through conchoidal fracture? Admittedly, we do not have the complete answers to these questions. However, we clearly demonstrate that knowing the exact consequence of a strike given to a core at hand inevitably requires the acute detection of the relevant features of a core and a hammerstone to comply with the constraints of conchoidal fracture, without which the organized *débitage* of flakes observed in some of the Early Stone Age sites may not have been possible.

Implications for human evolution

Mayr (1963: 604–605) wrote "a shift into a new niche or adaptive zone is, almost without exception, initiated by a change in behavior. The other adaptations to the new niche, particularly the structural ones, are acquired secondarily.... This is not the place to discuss how the behavior changes themselves originate, a problem still poorly understood." It has been repeatedly emphasized that changes in behavior that establish new environmental relationships often antedate genetic, physiological, or morphological changes, and today behavior is viewed as one of the leading edges of evolution, rather than simply its end product (Kuo, 1967; Plotkin, 1988; Gottlieb, 1992, 1997, 1998, 2002a,b; Iriki and Sakura, 2008). Examples of behaviorally-led niche shifts preceding genetic, physiological, or morphological change range from Japanese monkeys washing sweet potatoes (Kawai, 1965) to upland geese with webbed feet that never go near the water—which Darwin (1859: 186) described as "habits have changed without a corresponding change of structure." The recurrence of new environmental relationships may influence the selection pressures on species, favoring individuals with phenotypes that match the usage of novel behavioral resources of the environment (Lewontin, 1983/2001; Laland et al., 2000; Odling-Smee et al., 2003).

Whether or not this scenario can account for human evolution remains to be shown. But in any case, theories of evolution have to address the following general problems: (1) what allows for the establishment of a new environmental relationship, and (2) how does the relationship recur across generations. In the present study, we investigated a particular way of exploiting the environmental resources considered to have emerged in the Early Stone Age—the control of conchoidal fracture in flaking through direct hard-hammer percussion. Based on previous work on fracture mechanics (Dibble and Pelcin, 1995; Dibble, 1997), our study revealed that modern experienced stone knappers have discovered a regularity that exists in the relationship between platform variables, the dimension of a flake, and the threshold of kinetic energy required to initiate the fracture. This was demonstrated by their ability to control these variables by selecting striking location and controlling movement in such a way as to comply with the constraints of conchoidal fracture. Based on these results, we suspect that one of the requirements for the acquisition of controlled flaking was the ability of a knapper to discriminate the geometrical features of a core and distinguish one combination of such variables from another combination.

What, then, allowed this specific way of exploiting environmental resources to recur across generations? In the present study, only modern stone knappers with over twenty years of active knapping experience predicted flake dimensions that significantly correlated to those of detached flakes. The difficulty in controlling the shape of a flake implies that it requires skill learning to recur across generations. This further opens up the question of what the nature of this learning might have been.

Those who are able to control the shape of flaking are distinguished from those who are not by the ability to detect the constraints and opportunities offered by the environment—both the core and the hammerstone—for achieving the task at hand. Recent studies in psychology have shown that the ability to discriminate the functional properties of the environment for achieving a particular task often requires learning specialized exploratory strategies (Bingham et al., 1989; Reed, 1996; Wagman and Taylor, 2004; Zhu and Bingham, 2008; Arzamarski et al., 2010). The only way to know whether the shaved stick is supple enough to be used as a bow is to bend it in a specific way and feel its resilience (Reed, 1996). The only way to know whether a stone can be thrown to a certain distance is to heft it in a specific way (Bingham et al., 1989; Zhu and Bingham, 2008). In order to know how to control the kinetic energy of the hammerstone and how far its tip extends from the hand, an actor presumably needs to actually hold the object and wield it in a specific manner.

Regarding the perception of a core, the results of the current experiment suggest that expert knappers have learned to appreciate more of the features of a core, that is, they discriminate more of the observable variables and distinguish one combination of such variables from another combination. Expert knappers who are able to control the shape of a flake have learned how to identify the salient features of a core and its striking platform that influence flake morphology, which are not discriminated by less-skilled knappers. Essential to the acquisition of this ability is the first-hand experience to appreciate the detailed features of a core.

These requirements suggest that the skill of controlled flaking is not transmissible from one generation to the next independently of its application in the world. The recurrence of this specific way of exploiting the environment—the control of conchoidal fracture—may be the result of what Gibson (1979/1986: 253) called "education of attention" or what Ingold (1998/2001: 270) called "guided rediscovery." Here what needs to recur are situations in which the novice is afforded the possibility of unmediated experience, where one can rediscover constraints and opportunities directly, by looking at the surface of the core and wielding the hammerstone. Placed in a situation of this kind, which Reed (1993) and Reed and Bril (1996) referred to as a field of promoted action, the novice is encouraged to attend to this or that aspect of what can be seen, touched or heard, so as to get the feel of it for him or herself (Ingold, 1998/2001; Stout, 2002, 2005).

Given the considerable difficulty in controlling conchoidal fracture and the nature of the task, which requires seeking out the relevant features of the environment, we suggest that the recurrence of a learning situation which allows the transmission of the skill, possibly by providing the opportunities for first-hand experience, is likely to have been a prerequisite to the emergence of controlled flaking found in some Early Stone Age sites.

The role of exploration for affordances in stone knapping

Lastly, although we are not the first to see its potential for understanding tool use (e.g., Ingold, 1986; Reed, 1988b; Graves, 1990; Davidson and Noble, 1993; Roux et al., 1995; Stout, 2002; Wagman, 2002), we suggest that ecological psychology as developed by Gibson and colleagues (e.g., Gibson, 1966, 1979/1986; Turvey et al., 1981; Reed and Jones, 1982; Mace, 1986, 2005; Reed, 1987, 1988a, 1996) provides an appropriate framework for discussing those aspects of skill that could otherwise be neglected.

The great potential of Gibson's ecological psychology for improving our understanding of the development of tool use has often been obscured. The theories of perception comprising epistemic mediators (e.g., mental representations, mental images, etc.) postulate mental activities to supplement the sensory inputs or to correct, or interpret, or organize them, or make inferences from them, attach meanings to them, fuse them with memories, combine them with concepts, impose logic on them, or construct a model of the world from them (Gibson, 1976). But the theory of perception proposed by Gibson has a different emphasis. The emphasis of Gibson's (1967, 1973, 1976) theory is not on mental activity after the deliverance of senses but on activity before sensations have been aroused by stimuli, an activity that orients the organs of perception, explores the structured optical, acoustic, chemical fields, and hunts for information that specifies the behavioral resources available in the environment. Put differently, in Gibson' (1966) theory the emphasis is not on the state of the animal's *nervous system* upon the inputs of the sensory nerves but on the activity of *perceptual systems*, involving muscular effort, to optimize and hunt for information in optical, acoustic, and chemical fields surrounding the animal.

Note that this exploratory activity has no place in the mind-body dualism often assumed when discussing the development of stone tool-making. Contrasting ape technology with early stone knapping, for instance, Toth and Schick (1993: 351) wrote, "it may be beyond the cognitive capabilities of chimpanzees to modify stones in an Oldowan manner. The motor skills of the chimpanzee may be adequate for such operations…." Similarly, Pelegrin (2005: 23) wrote, "the control of conchoidal fracture is more a matter of understanding rules than of motor skill." Wynn (2002: 392) assumed the same dichotomy despite his contrary argument, "it is clear that fracturing stone is within the cognitive abilities of apes…. It could simply be a matter of biomechanical constraint (i.e., he does not have the necessary motor control)."

However, to simply say that skill is a matter of either "mental" or "biomechanical" may not lead in productive directions because the essence of the skill does not appear to be reducible to either one of these capacities. The evaluation of the stones and planning of action, on the one hand, is not reducible to mental activity but, as is the case with dynamic touch (Gibson, 1966; Turvey and Carello, 1995; Turvey, 1996), it requires adjustments of bodily movements to optimize and hunt for information. The control of action, on the other hand, is not reducible to bodily movements but requires being aware of the opportunities and constraints of the hammerstone and the core, such as the threshold of kinetic energy required to initiate the fracture (Bril et al., 2010). What is required seems to be the ability to optimize information that corresponds to the relevant features of the environment and the ability to control action according to the constraints and possibilities detected.

Fundamental to both is the active exploration to detect the features of the environment that correspond to the opportunities for action—what Gibson (1977, 1979/1986) called affordances of the environment. Along these lines, the increase of control over conchoidal fracture is indicative of the emergence of a system, of which learning situation, behavior of an organism, and other biological processes (e.g., genetic activity, neural activity) are components, that stabilizes the transmission of the detection of the constraints and opportunities for action in the environment across generations.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhevol.2010.04.006.

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