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NUMBER 3
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THE CUTTING EDGE:

New Approaches to the Archaeology of Human Origins

Editors

Kathy Schick
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Top: Homo habilis Utilizing Stone Tools. Painting by artist-naturalist Jay H. Matternes. Copyright 1995, Jay H. Matternes. Inspired by a prehistoric scenario by K. Schick and N. Toth in Making Silent Stones Speak: Human Origins and the Dawn of Technology (1993), Simon and Schuster, New York. Pp.147-149.

Lower right: Whole flake of trachyte lava from the 2.6 million-year-old site of Gona EG-10, Ethiopia. Reported by S. Semaw (2006), "The Oldest Stone Artifacts from Gona (2.6-2.5 Ma), Afar, Ethiopia: Implications for Understanding the Earliest Stages of Knapping" in The Oldowan: Case Studies into the Earliest Stone Age, eds. N. Toth and K. Schick. Stone Age Institute Press, Gosport, Indiana. Pp. 43-75. Photo courtesy of Tim White.

Lower left: Prehistoric cut-marks from a stone tool on Sterkfontein hominin partial cranium StW 53. Reported by T. Pickering, T. White, and N. Toth (2000) in "Cutmarks on a Plio-Pleistocene hominid from Sterkfontein, South Africa". American Journal of Physical Anthropology 111, 579-584. Scanning electron micrograph by N. Toth.

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CHAPTER 12

Understanding Oldowan Knapping Skill: An Experimental Study of Skill Acquisition in Modern Humans

Dietrich Stout, Kathy Schick and Nicholas Toth

Abstract

Variation in knapping skill is a potential source of variability in Oldowan artifact assemblages thought to have important cognitive, behavioral and evolutionary implications. However, a uniform method for assessing Oldowan knapping skill has yet to be adopted. Research presented here builds upon previous experimental and archaeological work in pursuit of increasingly systematic, detailed and empirically informed models of skill-related variation. Lithic products from six technologically naïve subjects, knapping before and after a controlled practice period, and from three experienced academic knappers were collected and analyzed as part of a broader experimental study of skill acquisition. Results revealed skill-related variation related to core reduction intensity, debitage productivity, frequency and morphology of fragments, flake metrics, and flake types, as well as modulation of these variables by raw material type and blank morphology. From this artifactual variation, three behavioral stages of skill acquisition were identified: I) an initial phase of relatively uncontrolled wedging fracture, II) a rapidly achieved phase of controlled but minimally invasive flaking, and III) expert performance with intensive core reduction through invasive flake removals. Of these, expert performance is most similar to patterns reported from early Oldowan artifact assemblages. These results highlight relevant variables and relationships to be considered in the archaeological evaluation of Oldowan knapping skill, and suggest the presence of substantial hominin investments in knapping skill acquisition already at this very early date.

Introduction

Assessing variation in hominin stone tool making skill is an increasingly important objective for Early Stone Age archaeology. In recent years, knapping skill has emerged as a key piece of evidence in a wide range of debates, including those over the existence of a "pre-Oldowan" technological stage (Roche, 1989; Semaw, 2000), the likelihood of hominin tool making prior to the earliest known occurrences (Panger et al., 2002; Semaw et al., 2003), the nature of variability in Plio-Pleistocene artifact assemblages (Delagnes & Roche, 2005; Kimura, 2002; Ludwig & Harris, 1998), the number of species involved in stone tool-making (Delagnes & Roche, 2005), and the sophistication of early hominin cognition and culture (de la Torre, 2004; Hovers, 2003; Ludwig & Harris, 1998; Roche, 2005; Semaw, 2000) in comparison to that of modern apes (Mercader, 2004; Pelegrin, 2005; Schick et al., 1999; Wynn & McGrew, 1989). However, no uniform method has been adopted for evaluating Oldowan knapping skill.

Major contributions to the subject have come from qualitative descriptions of East African Plio-Pleistocene lithic assemblages, including the reconstruction of reduction sequences (Delagnes & Roche, 2005) and strategies (de la Torre, 2004; de la Torre et al., 2003), as well as attribute-based evaluations of flaking skill (Ludwig & Harris, 1998; Semaw, 2000). In practical terms, this work has strongly supported the view (Semaw et al., 1997) that late Pliocene hominins were fully competent Mode I stone knappers. The adoption of an interpretive, "*chaîne operatoire*", approach by several of these studies (de la Torre, 2004; de la Torre et al., 2003; Delagnes & Roche, 2005) has also sought to introduce a new level of detail to the description and interpretation of Plio-Pleistocene technological behavior. This offers exciting possibilities for the reconstruction of specific knapping actions and strategies (Martinez-Moreno et al., 2003) while raising substantial new challenges for the study of behavioral variability. A suitably detailed comparative and explanatory framework is essential if we are to avoid producing a series of interesting but idiosyncratic case studies (Martinez-Moreno et al., 2003).

In this context, skill may be seen as one of many potential sources of inter-assemblage variability. Some of the assemblage characteristics putatively associated with knapping skill variation in the literature have included reduction intensity and efficiency (de la Torre, 2004; Delagnes & Roche, 2005; Ludwig & Harris, 1998; Semaw, 2000), flake size and morphology (de la Torre, 2004; Ludwig & Harris, 1998; Semaw, 2000), platform angles (Roche, 2005; Semaw, 2000), proportions of whole flakes vs. fragments (Hovers, 2003), frequency of hinge and step fractures (Kibunjia, 1994; Ludwig, 1999; Ludwig & Harris, 1998), standardization of knapping methods and products (de la Torre, 2004; de la Torre et al., 2003; Delagnes & Roche, 2005; Ludwig & Harris, 1998), and selectivity of raw materials (de la Torre, 2004; Ludwig & Harris, 1998; Stout et al., 2005). More recently, a systematic comparative study of Mode I knapping by Oldowan hominins, modern apes, and experienced modern humans (Toth et al., 2006) identified sixteen specific criteria for evaluating skill in Oldowan assemblages, including core type frequencies, scar counts, remnant cortex, and edge angles, as well as debitage type, frequency, mass, shape, and external platform angles. Importantly, results from this study also demonstrated the influence of broader behavioral patterns, such as test flaking at raw material sources, off-site core reduction, and the selective removal of artifacts, on relevant assemblage characteristics.

From such findings it is clear that a wide range of ancillary factors condition the expression, preservation and identification of even the most robust indicators of knapping skill. These include raw material characteristics and availability (de la Torre, 2004; Delagnes & Roche, 2005; Isaac, 1984; Ludwig & Harris, 1998; Semaw, 2000), artifact transport and discard patterns (Potts, 1991; Schick, 1987; Stiles, 1998; Toth, 1987), broader adaptive contexts (Blumenschine & Peters, 1998; Braun & Harris, 2003)[tackticos], site formation processes (Hovers, 2003; Petraglia & Potts, 1994; Schick, 1991), and even the "particular skills" (Gowlett, 2004) of individual lithic analysts. Thus, specific criteria used to assess knapping skill will frequently be incommensurate across sites. For example, reduction intensity is clearly related to skill but is also likely to be influenced by local raw material availability (Toth et al., 2006). For this reason, evaluation of relative knapping skill across assemblages has remained largely subjective (Plummer, 2004).

In order to move beyond such subjective assessments, it is necessary to develop more systematic, detailed and empirically informed models of skill-related variation. Ideally, such models would incorporate multiple interacting behavioral and environmental factors in order to assess demonstrated (i.e. minimum required) knapping skill at assemblage, regional and chronostratigraphic scales (Toth et al., 2006). Controlled knapping experiments with subjects of variable skill levels provide one major avenue for the development of such models. Logically, such studies may involve cross-sectional comparisons between groups and/or longitudinal investigations of skill acquisition within groups.

Cross-sectional studies are particularly useful in establishing an overall comparative framework and identifying relevant variables. Using such an approach, the aforementioned inter-species comparative study (Toth et al., 2006) situated archaeologically observed Oldowan knapping along a continuum between modern ape and human capabilities, suggested characteristics that might be expected in a hypothetical "pre-Oldowan" technological stage, and identified 16 specific indicators of knapping skill through a systematic assessment of 42 separate artifact attributes.

Longitudinal studies can complement such research by providing a window on the dynamics of skill acquisition, including novice performance, patterns of change through time, and amounts of practice required to achieve particular levels of skill. This last point is of considerable interest because the amount of practice time required for novices to replicate specific artifact forms might in principle be used as a quantitative measure of skill in archaeological assemblages (Toth, 1991). Prehistoric investments in technical skill acquisition may also have important cognitive, social and behavioral implications (Stout, 2002, 2005b).

Unfortunately, only a handful of experimental studies of Mode I knapping skill have been conducted (Ludwig, 1999; Ludwig & Harris, 1998; Toth et al., 2006) and none has directly investigated the process of skill acquisition. As a result, we still know very little about the behavioral dynamics, cognitive requirements and material correlates of Mode I knapping skill acquisition. For this reason, we undertook a multidisciplinary study of Mode I tool making skill acquisition in technologically naïve subjects, combining functional brain imaging (Stout & Chaminade, 2007), video-based operational analysis, and quantitative lithic analysis in order to gain a cohesive picture of the cognitive, behavioral and artifactual changes associated with skill acquisition. Lithic analyses, presented here, were aimed at identifying objective, quantitative indices of developing knapping skills that might be useful in modeling patterns of skill-related variation in the early archaeological record.

Experimental Design

Six novices with no prior stone knapping experience and three experienced academic knappers were recruited to participate in the study. Each novice subject participated in two Mode I knapping experiments (before and after practice) and each expert in one.

All knapping experiments were conducted under controlled conditions at the PET Imaging Center of the Indiana University School of Medicine, Department of Radiology. Subjects were seated in a chair with an array of stone cobbles available within easy reach on a cart to their left. Cobbles were collected at a gravel quarry in Martinsville, Indiana, and included a wide range of sizes, shapes and materials. Selection of cobbles (both hammerstones and cores) from those provided was an important component of the experimental task.

Subjects were instructed to use the cobbles on the cart to produce sharp stone flakes that would be "useful for cutting." This is in keeping with the current consensus that Oldowan knapping was primarily directed at the least effort production of sharp edges (Braun & Harris, 2003; Delagnes & Roche, 2005; Isaac, 1984; Potts, 1991; Toth, 1985), although it does not address the hypothesis that some core forms were intentionally shaped (Roche, 2005). At the outset of each experiment, a radiological tracer was administered through a venous catheter in the foot. Subjects were then left alone to perform the task for 40 minutes, after which time all lithic products were collected. A drop cloth was used to ensure 100% collection, and all experiments were video taped for operational analysis. As described elsewhere (Stout & Chaminade, 2007), brain activation data were collected following task completion.

After completion of the first experiment, each novice subject independently completed four weekly, uninstructed, 1-hour tool making practice sessions held at the Center for Research into the Anthropological Foundations of Technology (CRAFT) in Bloomington, Indiana. Subjects were provided with the same range of cobbles available during the experiments, as well as sheets of vinyl and pieces of wood with which to test the cutting ability of tools produced. Following completion of the practice regime subjects participated in a final tool making experiment with conditions and instructions identical to those in the pre-practice session.

Lithic Analysis

For each experiment, all lithic products greater than 25mm in maximum dimension were identified by raw material, technologically classified, and analyzed according to relevant technological attributes (Table 1, all analyses performed by DS). Previous research (Toth et al., 2006) has identified variables relating to reduction intensity, debitage productivity, flake size, and edge angles as being particularly relevant to knapping skill. In order to maximize the comparative utility of the analysis, an effort was made where possible to use variables that were quantitative rather than qualitative, continuous rather than categorical, and objective in the sense of being relatively easy to define, observe and replicate without reference to the particular expertise of the analyst.

Raw material classification

The first step in analysis was classification of the lithic raw materials. Nodules used in the study were collected from a gravel quarry in Martinsville, Indiana and included blocks of local sedimentary bedrock as well as glacial outwash from the White River. A wide array of rock types were represented in the sample, including micritic, silicified and variably fossiliferous limestones, siltstone, chert, quartz, quartz sandstone, quartzite, and various grades of metabasalt. Individual specimens within types further displayed substantial variation in technologically relevant characteristics including density, homogeneity, grain size, weathering, and the occurrence of internal flaws, inclusions and/or preferential fracture planes. This high level of variability resembles that observed in some East African Pliocene raw material sources (Stout et al., 2005), and presents similar difficulties for summary description and analysis.

In the current study, a highly conservative "lumping" approach was ultimately adopted, with each artifact being placed into one of three categories reflecting broad variation in flaking properties: 1) sedimentary (primarily limestone), 2) vein quartz, and 3) metamorphic (primarily quartzite and metabasalt). Chert, initially treated as a separate category, accounted for only 2.2% of the total number of artifacts and was ultimately grouped with other sedimentary rocks for analysis. A further 78 pieces (3.7%) were classified as unidentifiable or "other."

This inclusive classificatory scheme was adopted in order to maximize the robusticity, replicability and broader relevance of the results obtained. Information is necessarily lost regarding more specific raw material effects within categories, however any surviving trends and relationships will be those least sensitive to such variation. This is consistent with the goals of the current study, which focus on generalized model building rather than specific replication.

Nodule reconstruction

In order to avoid disturbing the experimental subjects, no attempt was made to separate the products of individual nodules during knapping. However, conjoining (assisted by the distinctive appearance of many nodules) allowed for over 95% of detached pieces to be assigned to their original nodule. In this way, each sample was treated as an idealized archaeological assemblage with 100% artifact representation.

Technological classification

Individual artifacts were initially classified into the basic technological categories proposed by Isaac (1984): flaked pieces, detached pieces and pounded pieces (Table 1). In order to provide additional descriptive detail, flaked pieces were further classified using the modified version of Mary Leakey's (1971) typology developed by Toth (1985; 1982). Although categorical and qualitative, these classifications are easily defined and reproduced

Table 1. Variables used in lithic analysis

Technological Classification		**Technological Attributes**		
Flaked and Pounded Pieces*	**Detached Pieces**	**Cores**	**Whole Flakes**	**Angular Fragments**
Battered cobble	Whole Flake	Length (mm)**	Maximum Dimension (mm)	Length (mm)**
Casual core	Split Flake	Breadth (mm)	Length (mm)	Breadth (mm)
Unifacial chopper	Proximal Snap	Thickness (mm)	Breadth (mm)	Thickness (mm)
Bifacial chopper	Angular Fragment	Mass (g)	Thickness (mm)	Mass (g)
Unifacial discoid		Remaining Cortex (%)	Mass (g)	
Bifacial discoid			Platform Breadth (mm)	
Core scraper			Platform Thickness (mm)	
Polyhedron			Exterior Platform Angle (EPA)	
Split cobble			Flake Type	

** Only types actually present in the sample are listed*
*** For cores and angular fragments, length is defined as the maximum dimension*

by different analysts and provide a rough indication of both mode and intensity of reduction (Toth, 1985; Toth, 1982).

Detached pieces were classified as whole flakes, split flakes (longitudinal fracture), proximal snaps (transverse fracture, with striking platform preserved) and angular fragments (no striking platform). Although it is sometimes possible to further differentiate angular fragments as flake fragments (distal snaps, midsections, etc.) or angular shatter (e.g. "chunks"), this introduces an additional level of subjectivity to the analysis and was not attempted here. Instead, the ratio of maximum dimension to thickness was used to provide an objective and continuous measure of fragment laminarity vs. chunkiness.

Technological attributes

Technological attributes recorded for all artifacts > 25mm in maximum dimension are listed in Table 1.

Cores

Cores were analyzed according to linear dimensions, mass, and % cortex coverage. Length was defined as the maximum dimension, with breadth as the maximum dimension orthogonal to length and thickness as the maximum dimension perpendicular to the plane defined by length and breadth. Core mass was measured to the milligram.

With regard to skill, it was considered that the most important variables potentially represented by cores were flaking mode (reflected in technological classification) and reduction intensity. Reduction intensity has been linked with flake scar counts (Potts, 1991; Toth, 1982), however this relationship is complicated by the effects of initial core size and the deletion of scars by subsequent flake removals (Braun et al., 2005). Exact scar counts may also be difficult to replicate (Andrefsky, 1998), particularly in coarse and/or shatter-prone materials. Experience with conjoining in the current experimental sample clearly showed that apparent scar counts were frequently misleading regarding the actual number and pattern of detachments, particularly in the novice samples.

For these reasons, the simpler measure of percent cortex coverage (estimated to the nearest 5%) was adopted. Although subject to some of the same limitations as flake scar counts, this measure is easily defined, rapidly recorded and reasonably predictive of reduction intensity. In the current sample, % cortex predicted the total number of detached pieces per nodule with an $r^2 = 0.48$.

Whole flakes

Whole flakes were analyzed for linear dimensions, platform dimensions, external platform angle, mass, and flake type. Linear dimensions and mass provide information regarding flake size and shape, both of which have been linked with knapping skill (Ludwig, 1999; Ludwig & Harris, 1998; Semaw, 2000; Stout, 2002; Toth et al., 2006). Length was defined as the distance from the point of percussion, perpendicular to platform breadth, to the distal margin of the flake, while breadth and thickness were defined as maximum dimensions orthogonal to length. These particular definitions were selected because they are easily defined, measured and replicated, and because they reflect information about flake shape not captured by measurements like "maximum flake length" (Andrefsky, 1998). Ratios were used as a quantitative and continuous means to assess variation in flake shape, including laminarity (maximum dimension/thickness), elongation (breadth/length), and skewing (displacement of the maximum dimension away from the axis of either length or breadth).

Flake platform dimensions (breadth and thickness) are theoretically interesting because they are (at least potentially) under the control of the knapper and are causally related to flake size (Dibble, 1997; Dibble & Pelcin, 1995; Speth, 1972). Manipulation of platform dimensions is one way in which skilled knappers might exert control over the knapping process. Platform breadth was defined as the distance between the lateral margins of the flake along the striking platform. Platform thickness was defined as the distance along the platform surface between the dorsal and ventral margins at the point of percussion.

External Platform Angle (EPA) is another important variable that may be manipulated by knappers in order to influence the size and shape of flakes (Dibble, 1997; Dibble & Pelcin, 1995; Speth, 1972), and the amount of force required to successfully initiate fracture (Dibble & Pelcin, 1995). Selection and maintenance of appropriate core angles is an important factor in knapping success (Pelegrin, 2005), and a relationship between EPA and knapping skill level has been documented in previous ethnographic and experimental research (Ludwig, 1999; Stout, 2002). Unfortunately, flake platform angles are notoriously difficult to define and measure in a reliable fashion (Andrefsky, 1998; Cochrane, 2003; Dibble, 1997). Mode I flakes do have the advantage of relatively large and simple platforms compared to some more recent technologies (Cochrane, 2003), however they frequently display highly irregular and convex dorsal surfaces. For this reason, measurements taken to well-defined and consistent dorsal landmarks (for example, to a point located below the platform at a distance equal to platform thickness [Dibble, 1997]) may be less effective in Mode I flakes. In particular, such measures (Figure 1a) may fail to capture physical relationships influencing Mode I flake size and shape. As explained by Dibble and Pelcin (1995), the relationship between EPA and flake size may be conceptualized in simple geometric terms, with increases in EPA producing triangular flake cross sections of increasing height and area (figure 1b). Although cross sections of real flakes inevitably deviate from this geometric ideal, the underlying relationships are expressed by a right triangle drawn between the striking platform and dorsal flake surface (Figure 1c). The base (striking platform) and hypotenuse of this triangle form an EPA that is determined by the overall distribution of mass in the flake, rather than by the flake's proximal dorsal morphology. This angle is reflective of the underlying mechanics of flake removal and, in more subjective terms, approximates judgments of effective edge angle made by knappers confronted with superficially irregular core morphologies.

Unfortunately, dorsal convexities frequently make it impossible to measure this angle directly on flakes. In the current study, measurements (to the nearest 5°) were taken by aligning the goniometer arm along a line parallel to the hypotenuse and tangent to the dorsal surface (Figure 1c). Although this angle captures important technological information, the method of its measurement is clearly dependant on the individual skills of the analyst. Until a better method is developed, perhaps through the use of digital image analysis, a degree of subjectivity and imprecision in this measure is unavoidable.

In order to assess the accuracy of the current method of measurement, a replication study was conducted with a random sample of 96 flakes from 10 different nodules. Re-measurement yielded a difference in the mean EPA of 0.5° with no change in the median value, confirming

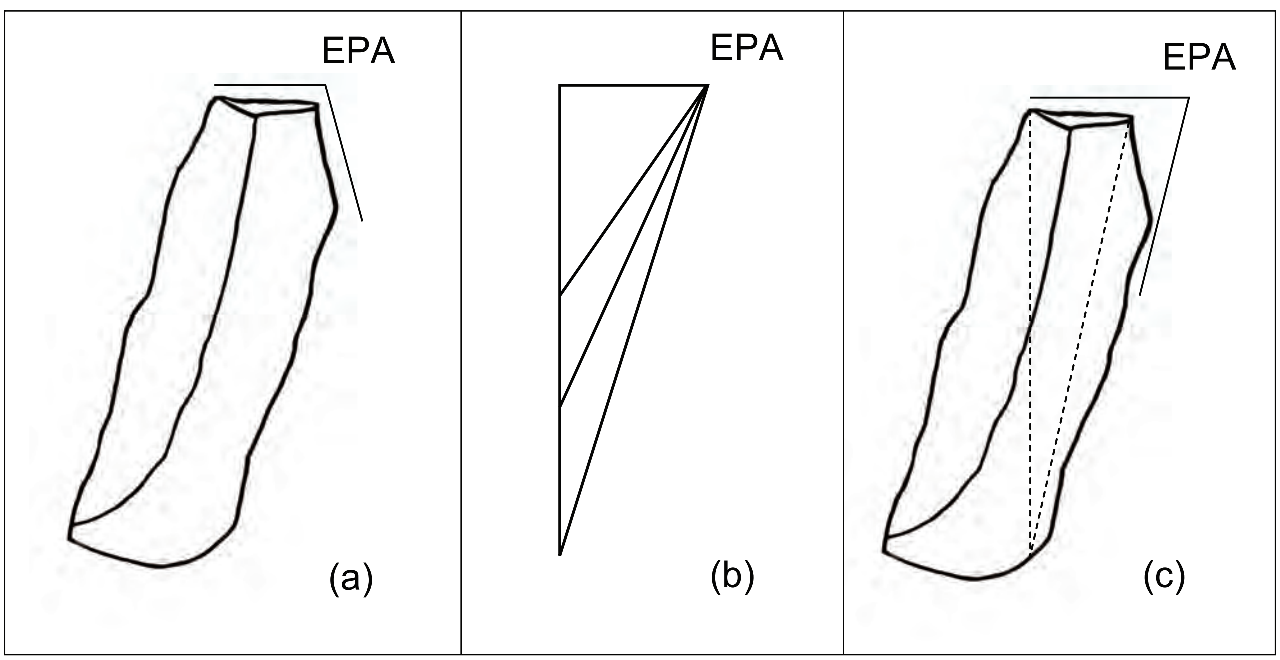

Figure 1. Measuring the External Platform Angle on a large type IV flake from the expert sample: (a) a direct measurement, (b) underlying geometric relationship of EPA to flake size, (c) method of measurement adopted in this study.

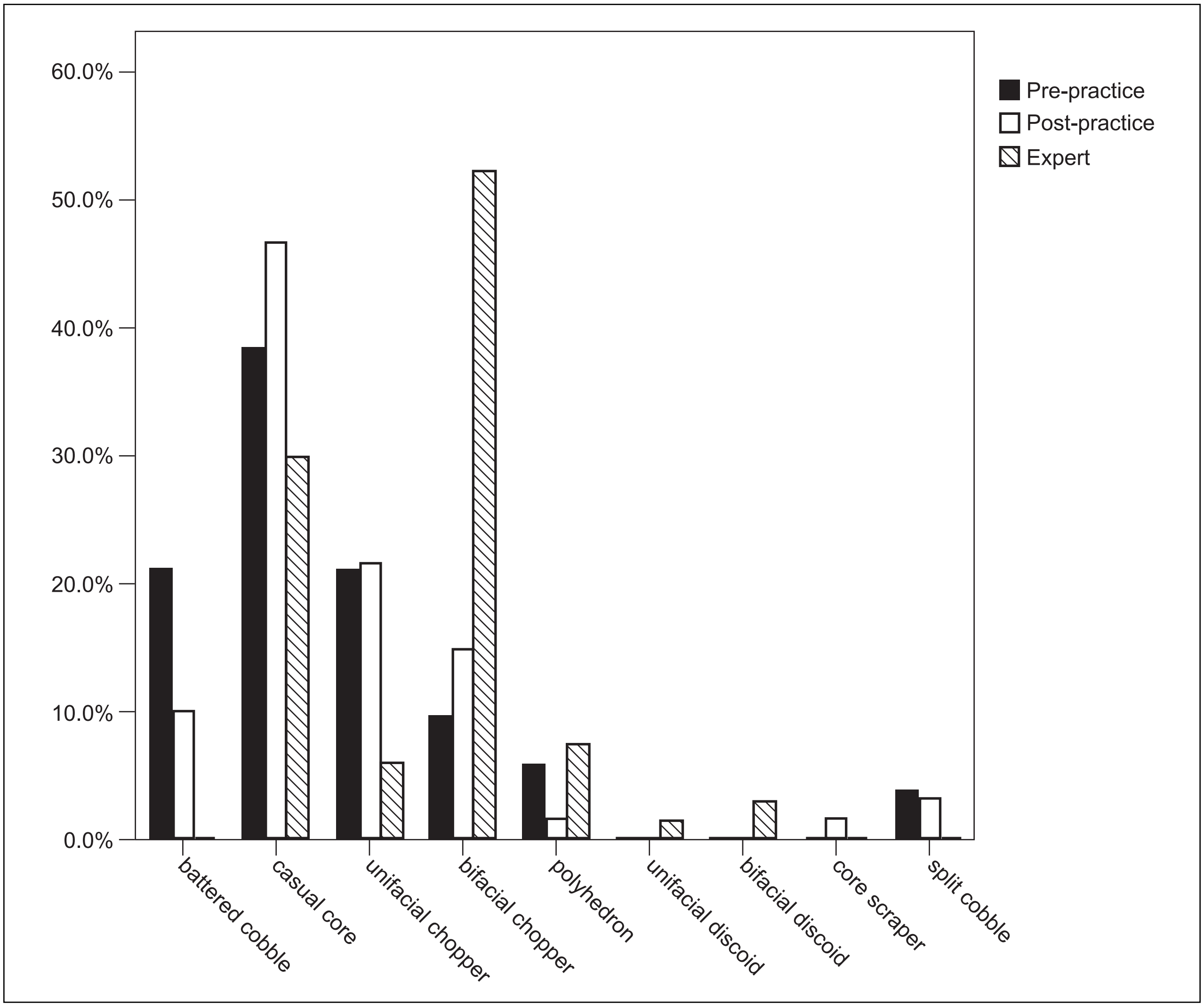

Figure 2. Core type representation in novice and expert samples

the replicability of the central tendency. The mean error was 4.9° with a median and a mode of 5.0°. This likely reflects the fact that measurements were taken to the nearest 5.0°.

Angular fragments

Angular fragments were analyzed for linear dimensions and mass. Due to the lack of technological landmarks, length was defined as the maximum dimension, with breadth as the maximum dimension orthogonal to length and thickness as the maximum dimension perpendicular to the plane defined by length and breadth. Mass was measured to the milligram.

Other fragments

The other fragment categories used in this study were split flakes and (proximal) snapped flakes. Split and snapped flakes were analyzed for maximum dimension, length, breadth, thickness and mass in the same fashion as whole flakes, with the obvious difference that some measures (breadth for split flakes, length for snaps) were being taken to broken edges rather than intact margins. In addition proximal snaps were analyzed for platform dimensions and EPA. Fragments that were both split and snapped were treated as angular fragments.

Statistical Analyses

All statistical analyses were conducted using SPSS©. Variables analyzed for this study include both categorical (e.g. core and debitage types) and ratio (e.g. artifact counts, flake metrics) data. The significance of variation between samples in the distribution of categorical data was tested using Pearson's Chi-Square. In the case of ratio data, there was no strong reason to expect homogeneity of variance on any of the variables being examined. Thus, following Ruxton (2006), it was decided to apply the unequal variance (Welch) t'-test for all significance testing on ratio data. It is also quite typical for debitage metric attributes to be heavily skewed by a preponderance of small pieces. This was the case in the current study, and many sample distributions were found to be significantly non-normal (1-sample Kolmogorov-Smirnov test, $p < 0.05$). In these cases, data were ranked before application of the t'-test (Zimmerman & Zumbo, 1993), and median values used to report central tendency.

Table 2. Productivity by Experience and Raw Material

Experience	Raw Material	Cobbles	WF	AF	Flake Fragments		DP
					SF	PS	
Pre-Practice (n=6)	Sedimentary	21	95 31%	178 58%	31 10%	4 1%	308
	Quartz	11	16 39%	24 58%	1 2%	0 0%	41
	Metamorphic	20	84 57%	49 33%	14 9%	1 1%	148
	Total	*52*	*195* *39%*	*251* *51%*	*46* *9%*	*5* *1%*	*497*
Post-Practice (n=6)	Sedimentary	27	98 45%	83 38%	34 15%	5 2%	220
	Quartz	13	33 28%	55 47%	26 22%	2 2%	116
	Metamorphic	19	67 53%	29 23%	24 19%	7 6%	127
	Total	*59*	*198* *43%*	*167* *36%*	*84* *18%*	*14* *3%*	*463*
Expert (n=3)	Sedimentary	10	117 38%	119 38%	61 20%	14 5%	311
	Quartz	7	34 49%	29 41%	6 9%	1 1%	70
	Metamorphic	48	263 42%	213 34%	118 19%	27 4%	621
	Total	*65*	*414* *41%*	*361* *36%*	*185* *18%*	*42* *4%*	*1002*

**Table does not include the small number of artefacts classified as "indet/other"*

Results

Analysis of the technological attributes described above produced evidence of skill-related variation in core reduction, flake productivity, frequency and morphology of fragments, flake metrics, and flake types. Important raw material effects were observed, as well as skill effects that are relatively independent of raw material.

Core reduction

The frequency distribution of core types (Figure 2) showed little change in novices before and after practice (Pearson Chi-Square 5.57, df = 6, $p = 0.473$), but in experts reflected a much greater representation of bifacial and more heavily reduced (polyhedral, discoidal) forms (Pearson Chi-Square 60.99, df = 16, $p < 0.001$). The same pattern is seen in the percentage of cortex ocverage, which is indistinguishable among novices, but significantly less in experts (median = 60%) compared to pre-practice (median = 75%, $t' = 3.52$, df = 98.51, $p = 0.001$) and post-practice (median = 78%, $t' = 4.18$, df = 123.03, $p < 0.001$) novices. This difference is also significant in each raw material category consider separately. The only apparent trend within novices is a decrease in battered cobbles and concomitant increase in casual cores (i.e. indicating greater success in removing at least one or two flakes) following practice (Figure 2).

Productivity

Artifact productivity by experience level and raw material type is reported in Table 2. Among novices, practice was not associated with any significant changes in overall productivity, whether measured in terms of to-

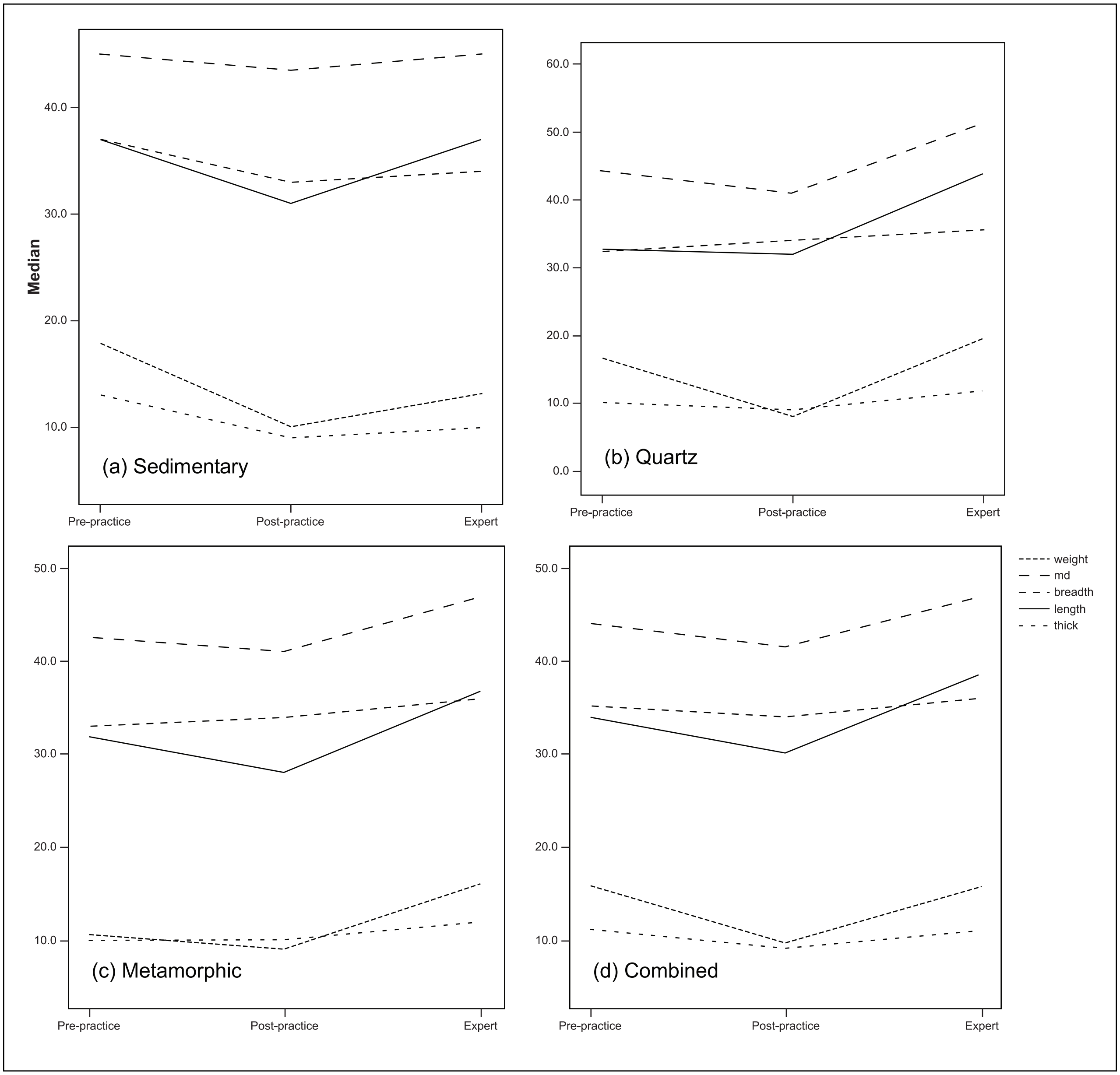

Figure 3. Effects of experience on flake size in different raw materials.

tal cobbles modified, pieces detached, whole flakes produced, pieces detached per cobble or whole flakes produced per cobble. There was also no major alteration in the proportions of sedimentary, quartz and metamorphic cobbles modified (0.40:0.21:0.39 vs. 0.46:0.22:0.32).

In contrast, expert subjects modified significantly more cobbles than pre-practice ($t' = -3.26$; $df = 2.49$; $p = 0.062$) and post-practice ($t' = -5.55$; $df = 4.11$; $p = 0.062$) novices, detached more pieces (pre: $t' = -4.15$; $df = 3.46$; $p = 0.019$ / post: $t' = -4.55$; $df = 2.68$; $p = 0.025$) and produced more whole flakes (pre: $t' = -3.51$; $df = 2.54$; $p = 0.051$ / post: $t' = -3.61$; $df = 2.24$; $p = 0.058$). Changes in productivity per cobble in the total sample were not significant, however this likely reflects raw material differences relating to the much greater percentage of metamorphic cobbles (72%) modified by experts. Experts did produce significantly more whole flakes (pre: $t' = -2.73$; $df = 22.71$; $p = 0.012$ / post: $t' = -3.06$; $df = 17.78$; $p = 0.007$) and detached pieces (pre: $t' = -3.38$; $df = 28.91$; $p = 0.002$ / post: $t' = -5.97$; $df = 28.16$; $p < 0.001$) per sedimentary cobble and per quartz cobble (whole flakes: $t' = -3.51$; $df = 15.98$; $p = 0.003$/ $t' = -2.24$; $df = 17.34$; $p = 0.039$; detached pieces: $t' = -2.43$; $df = 14.60$; $p = 0.028$/ n.s. in comparison to post-practice). Increased productivity of flakes and detached pieces per metamorphic cobble was significant at a lower threshold (whole flakes: $t' = -1.78$; $df = 28.84$; $p = 0.085$/ $t' = -1.87$; $df = 26.27$; $p = 0.073$; detached pieces: $t' = -1.76$; $df = 30.98$; $p = 0.089$/ $t' = -2.03$; $df = 32.37$; $p = 0.050$).

Fragments

In the sample of all novice fragments, practice was associated with a significant decrease in mass, absolute thickness and an increase in laminarity (maxi-

Table 3. Median values for all fragments

Raw Material	Experience	Max. Dim.	Breadth	Thickness	Max. Dim./ Thickness	Mass	% SF
Sedimentary	Pre-practice	37.7	27.5	13.6	3.9	8.9	1.4
	Post-practice	39.0	26.7	13.3	4.1	8.0	7.6
	Expert	38.0	27.8	13.6	4.0	7.4	18.5*
Metamorphic	Pre-practice	40.7	26.5	13.8	3.8	7.0	5.8
	Post-practice	39.4	26.4	11.6	4.3	5.9	0.0
	Expert	39.0	23.9	10.2*	4.5*	6.0	11.0
Quartz	Pre-practice	41.0	25.8	11.9	4.2	8.1	0.0
	Post-practice	40.5	26.3	10.2	4.7	6.5	7.7
	Expert	39.0	21.9†	8.7	4.6	4.3*	20.0*
Combined Sample	*Pre-practice*	*37.0*	*23.0*	*11.0*	*3.4*	*8.5*	*0.0*
	Post-practice	*37.0*	*23.0*	*10.0**	*3.8**	*7.0**	*0.0*
	Expert	*35.0*	*22.0***	*9.0**	*4.0**	*6.1**	*13.6**

** Significantly (p<0.05) different from pre-practice novices*
† Significantly (p<0.05) different from post-practice novices
*** Significantly (p<0.05) different from pre- and post-practice novices*

Table 4. Median values for whole flakes

Raw Material	Experience	Max. Dim.	Length	Breadth	Breadth/ Length	Thick-ness	MD/ Thick-ness	Mass	Plat-form Breadth	Plat-form Thick-ness	EPA
Sedimentary	Pre-practice	49.8	38.0	37.6	1.08	14.0	3.84	20.6	26.0	10.0	80.0
	Post-practice	45.0*	32.0*	35.0*	1.06	11.0*	4.52*	13.0*	21.0	8.0	80.0
	Expert	45.0	37.0†	34.0	1.09**	10.0	4.33*	13.0	22.0	7.0	75.0**
Metamorphic	Pre-practice	41.9	31.7	33.1	1.09	10.0	4.17	10.7	20.0	7.0	90.0
	Post-practice	41.0	28.0	35.0	1.15	11.0	4.25	11.6	23.0	8.0	85.0*
	Expert	50.0**	40.0**	36.5	0.93**	12.0	4.33	19.6**	23.0	7.0	80.0**
Quartz	Pre-practice	45.8	33.0	31.8	1.14	10.3	4.44	16.8	20.5	6.5	80.0
	Post-practice	39.0	32.5	32.0	1.04	10.0	4.29	8.0	21.0	5.0	85.0
	Expert	52.5	44.5†	35.5	0.92†	12.0	4.10	21.8	18.0	4.0	85.0
Combined Sample	*Pre-practice*	*45.6*	*35.0*	*35.6*	*1.10*	*11.9*	*4.00*	*17.0*	*22.8*	*8.0*	*85.0*
	Post-practice	*42.5*	*31.0**	*35.0*	*1.08*	*10.5**	*4.48**	*18.4**	*22.5*	*7.0*	*80.0**
	Expert	*49.0†*	*40.0***	*36.0*	*0.93***	*12.0†*	*4.30*	*16.7†*	*22.0*	*7.0*	*80.0**

** Significantly (p<0.05) different from pre-practice novices*
† Significantly (p<0.05) different from post-practice novices
*** Significantly (p<0.05) different from pre- and post-practice novices*

mum dimension/thickness). Expert fragments differed significantly from post-practice novice fragments only in breadth, perhaps reflecting the increased production of split flakes. The proportion of split flakes relative to the total number of pieces detached per cobble showed a progressive increase from pre-practice (mean rank = 68.7) to post-practice (mean rank = 78.4) to expert (mean rank = 91.0), however this difference was only significant in the comparison of experts to pre-practice novices ($t' = -2.66$, df = 81.86, $p = 0.01$). Split flakes in general were larger (maximum dimension: $t' = -2.69$, df = 609.76, $p = 0.007$) and relatively thinner ($t' = -4.54$, df = 651.15, $p < 0.001$) than angular fragments.

Analysis by raw material category inevitably reduced sample sizes, particularly in the case of the quartz and novice metamorphic samples (Table 2). Within individual raw material categories, changing median values (Table 3) are consistent with skill-related changes in fragment size and shape, but generally fail to achieve significance at the $p < 0.05$ threshold. Exceptions include the decreased mass of expert quartz fragments relative to pre-practice novices, and the decreased absolute and relative thickness of expert metamorphic fragments compared to those of pre-practice novices. The percentage of split flakes increases significantly in experts compared to pre-practice novices for sedimentary and quartz, but not for metamorphic, cores.

Whole flakes

Metrics

Analysis of the total sample of whole flakes (Table 4; Figure 3d) indicates a significant decrease in the length, thickness, relative thickness, mass and EPA of novice flakes following practice. Expert flakes reverse this trend toward reduced size, returning to pre-practice values for mass, maximum dimension and thickness, as well as being both longer and more elongated (breadth/length) than either sample of novice flakes. No significant trends were observed in platform dimensions; however the novice samples did have a much higher percentage of flakes lacking well-defined platforms (i.e. having broken, linear or punctiform platforms) on which measurements could be taken. These account for 16% of pre-practice flakes, 23% of post-practice flakes and 9% of expert flakes. The EPA of expert flakes was statistically indistinguishable from the post-practice condition.

As in the fragments, trends in flake size and shape seen in the total sample appear to be reflected within raw material categories (Figure 4a-c) although apparent differences are not always statistically significant in these reduced samples (Table 4). Quartz in particular is characterized by small sample sizes, and achieves significance only in comparisons of expert length and elongation to post-practice novices.

Among sedimentary flakes, maximum dimension, length, breadth, thickness, relative thickness and mass are all significantly reduced in post-practice flakes compared to pre-practice flakes. Expert sedimentary flakes show no significant differences in size from pre-practice novices, but are relatively thinner and more elongated. Expert sedimentary flakes also have a lower EPA than either novice sample.

Among metamorphic flakes, the only significant difference between pre- and post-practice novices is a reduction in EPA. Expert metamorphic flakes show a further reduction in EPA, as well as significantly greater maximum dimension, length, elongation, and mass than either novice sample.

Shape

Variation in the ratio of flake breadth to length at all skill levels is unimodal and continuous, providing no evidence of discrete morphological categories. In novice flakes, both before and after practice, breadth/length ratios cluster around 1.0, with median values of 1.08 and 1.10 respectively. In each case, more than half (62%, 60%) of flakes display a breadth greater than or equal to length. As described above, expert flakes are significantly more elongated, with length exceeding breadth in 55% of flakes (median = 0.94). In all samples, flake maximum dimension rarely exceeds the hypotenuse of a triangle formed by length and breadth (pre-practice = 9%, post-practice = 12%, expert = 12%), reflecting an infrequent occurrence of “skewed” flake shapes. There are no significant differences between any of the samples on this ratio.

Flake types

As may be seen in Figure 4, pre- and post-practice novice samples are dominated by flakes with cortical platforms (Types I-III) while experts show an increased representation of Type V. There is no significant difference between novice flake type distributions (Pearson Chi-Square = 8.84, df = 5, $p = 0.116$), however the expert distribution is significantly different from both pre-practice (Pearson Chi-Square = 14.17, df = 5, $p = 0.015$) and post-practice (Pearson Chi-Square = 42.13, df = 5, $p < 0.001$) novices. The same pattern ($p < 0.05$) is present in the sedimentary and metamorphic samples considered separately. Unfortunately, the quartz samples are too small (pre-practice = 16, post-practice = 27, expert = 34) for separate evaluation.

A one-way ANalysis Of VAriance on ranked data shows a significant interaction ($p < 0.005$) of flake type with each of the metric variables and ratios presented in Table 4. As shown in Figure 5, this reflects the relatively large size of types I, II and V relative to types III, IV, and VI. Among this first group, linear, mass and ratio differences between experience levels reported in Table 4 remain significant at $p < 0.05$ (novices vs. experts) and $p < 0.10$ (pre- vs. post-practice) thresholds. However, this is not the case in the second group, in which only the greater length and elongation of expert flakes vs. post-practice novices remains significant ($p < 0.05$). The proportion of the total sample represented by these two groups of flakes is essentially constant across experience levels (pre-practice: 0.68/0.32, post-practice: 0.68/0.32, expert: 0.67/0.33).

EPA behaves differently across flake types in experts as compared to novices (Figure 6), specifically in the much more acute EPAs of expert non-cortical platform flakes (types IV – VI). This pattern, coupled with the greater representation of non-cortical platform flakes in the expert sample, accounts for the reduced EPA of expert vs. novice flakes seen in Table 4. When non-cortical platform flakes are removed from the analyses, these differences disappear.

Discussion

Expert performance

The most striking patterns observed in the current study are the vastly greater debitage productivity and core reduction intensity of experts compared with novices. Half the number of experts produced more than twice the number of detached pieces in the same amount of time (Table 2), removed a significantly greater percentage of cortex from each core, and produced many more highly modified core forms (Figure 2). Somewhat surprisingly, 4 hours of practice did not result in any increase in the overall productivity or reduction intensity of novices and was actually associated with a decrease in the size of flakes (Table 4; Figure 3). This is in stark contrast to experts, who produced flakes that were not only more numerous, but also larger and more elongated. This is important because the greater size and invasiveness of flakes detached by experts is directly related to their increased productivity and reduction intensity.

In order to establish and maintain viable (i.e. relatively flat) knapping surfaces on a Mode I core, it is necessary to strike invasive flakes (Delagnes & Roche, 2005), ideally traveling more than half way across the surface. In contrast, the removal of small, non-invasive flakes from core edges leads to a progressive rounding of surfaces, creation of more obtuse edge angles, and premature exhaustion of the core. The production of sufficiently invasive flakes is itself dependant on the perceptual-motor and strategic skills of the knapper, who

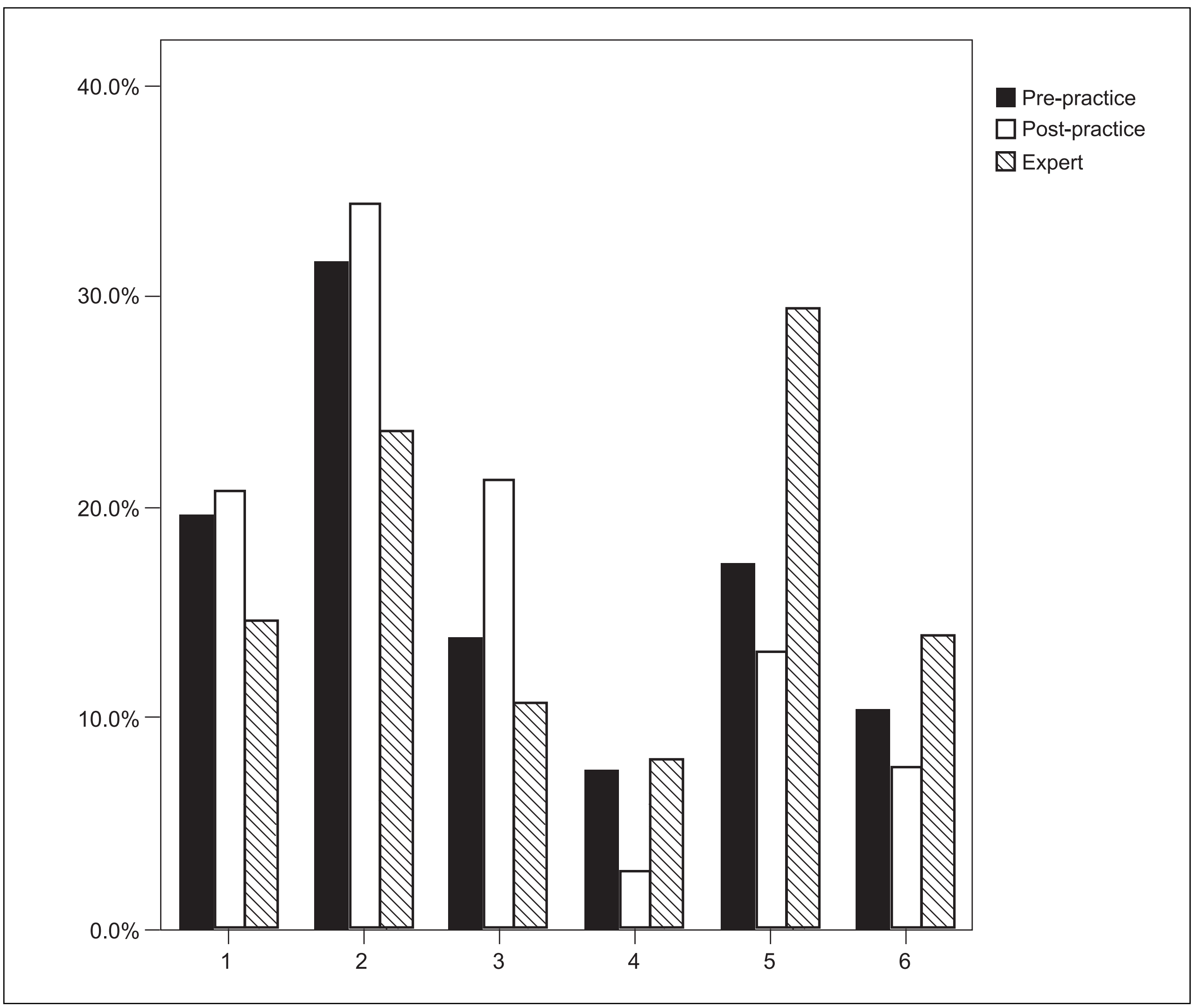

Figure 4. Flake type representation in novice and expert samples

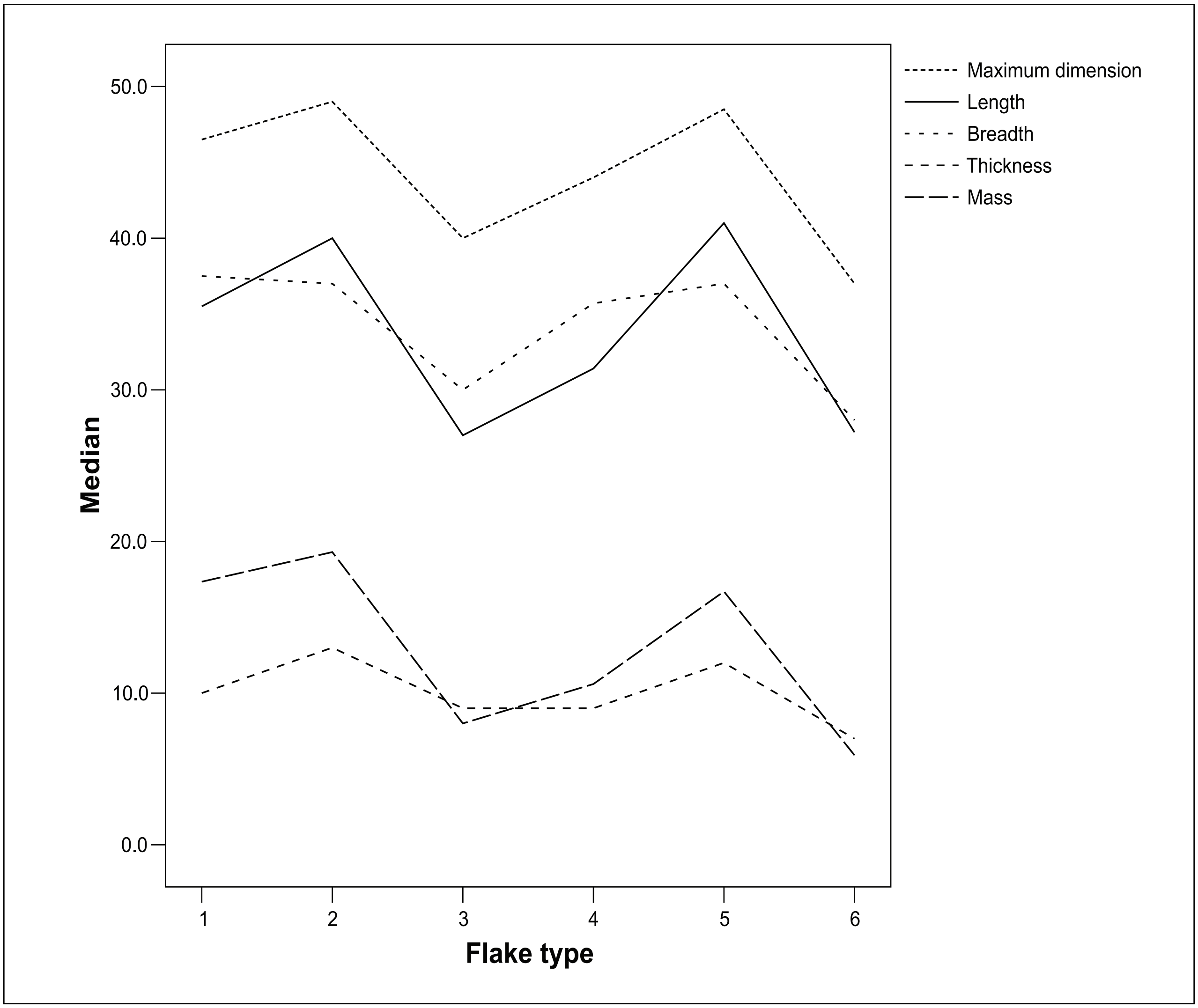

Figure 5. Relationship of flake type to flake size.

must accurately deliver sufficient force to appropriately selected targets.

All other things being equal, detachment of increasingly large flakes requires increased percussive force (Dibble & Pelcin, 1995). This may be achieved through an increase in strike velocity, an increase in hammer mass, or some combination of the two. Unless accompanied by a proportional decrease in accuracy, such changes constitute an increase in the motor difficulty of the task (Fitts, 1954), and require commensurate increases in perceptual-motor skill. However, invasiveness is also a function of the shape of flakes, as flakes that are massive but short (i.e. relatively broad and/or thick) may still fail to invade the center of the knapping surface. Flake thickness is related to platform thickness ($r^2 = 0.52$ in the current sample) while relative elongation is a function of the EPA (Figure 1b) together with the topography of the knapping surface. The latter relationship reflects the fact that flakes will travel longitudinally along ridges but tend to spread laterally across flat surfaces (Whittaker, 1994).

Expert knappers were able to manipulate all of these variables in order to produce larger, longer, and more numerous flakes and more heavily reduced cores. Particularly striking is the greater prevalence of bifacial cores (Figure 2) and non-cortical platform flakes (Figure 4) in the expert sample. This reflects that fact that, through controlled flake removals, experts proactively created viable flaking surfaces rather than simply exploiting the natural surfaces of the core. This allowed experts to produce advantageous (75±5° [Pelegrin, 2005]) edge angles (Figure 6) for bifacial flake removals and to maintain large median sizes in non-cortical platform flakes (Figure 5).

Novice performance

Novice subjects were clearly challenged by the basic physical requirements of flake detachment, and never developed the perceptual-motor skill required for the bold, invasive flaking seen in experts. Because of this constraint, novices were unable to exert the same degree of control over flake size and shape and thus had little control over core form. The relatively brief period of practice encompassed by the experiments instead documents an earlier and more fundamental step in skill acquisition: the transition from relatively uncontrolled

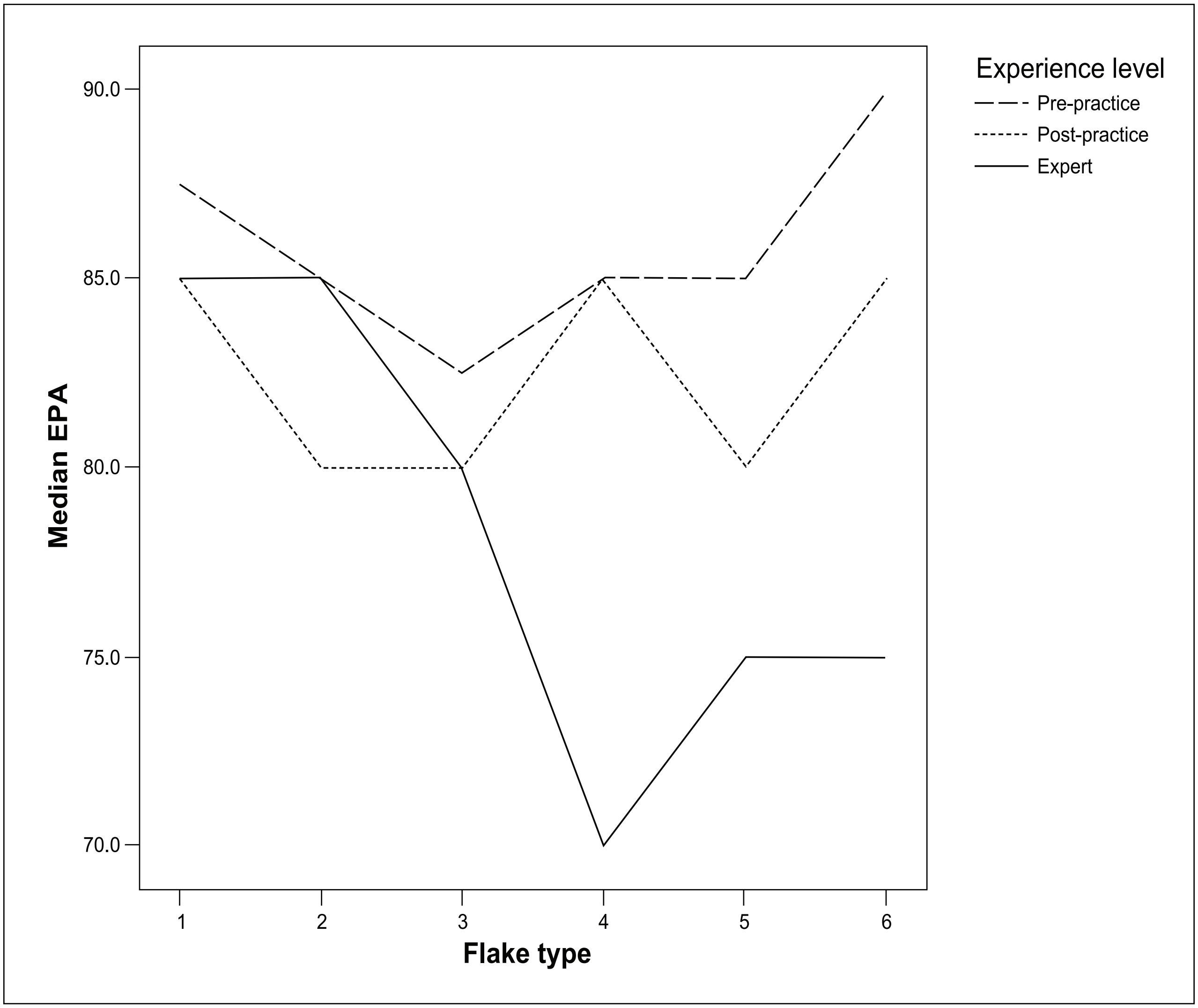

Figure 6. Relationship of flake type to External Platform Angle by experience level.

fracture of rock using brute force to more intentional flake production based on the deliberate exploitation of core morphology (Figure 7).

As described by Pelegrin (2005), it is possible to fracture rock without any particular regard to core morphology, so long as the percussive force applied is great enough. Indiscriminate blows, if directed away from core edges or toward obtuse angles, will commonly result in the initiation of wedging (Cotterell & Kamminga, 1990) or "split" fractures and tend to produce large numbers of amorphous angular fragments with only the occasional flake or flake fragment. More consistent production of conchoidal flakes is achieved through Hertzian fracture initiated near acute core edges (Cotterell & Kamminga, 1990), a technique which requires greater percussive precision, bi-manual coordination and technical understanding (Pelegrin, 2005). In the current study, an increased reliance on conchoidal fracture technique following practice is indicated by proportional decreases in the production of angular fragments, seen within each raw material category as well as in the combined sample (Table 2).

This shift in technique was also associated with significant changes in flake morphology in sedimentary and metamorphic materials, including reductions in flake size, thickness and EPA that relate directly to the requirements of Hertzian fracture. No such changes were documented in quartz, which may reflect the particular fracture properties of quartz (e.g. Knight, 1991) or simply the small size of the quartz sample.

The sedimentary sample was dominated (80%) by blocks of limestone bedrock offering relatively acute natural edge angles and forgiving fracture mechanics (Sahnouni et al., 1997). As a result, it was often possible for pre-practice novices to initiate fracture with blows struck a considerable distance from core edges and to produce large, relatively thick conchoidal flakes (Table 4; Figure 3) along with prolific angular fragments (Table 3). After practice, greater control was achieved by striking closer to core edges, preferentially producing smaller, thinner flakes accompanied by less than half as many angular fragments. Due to clast shape and fracture properties, EPA does not appear to have been an important constraint on sedimentary flake production and only

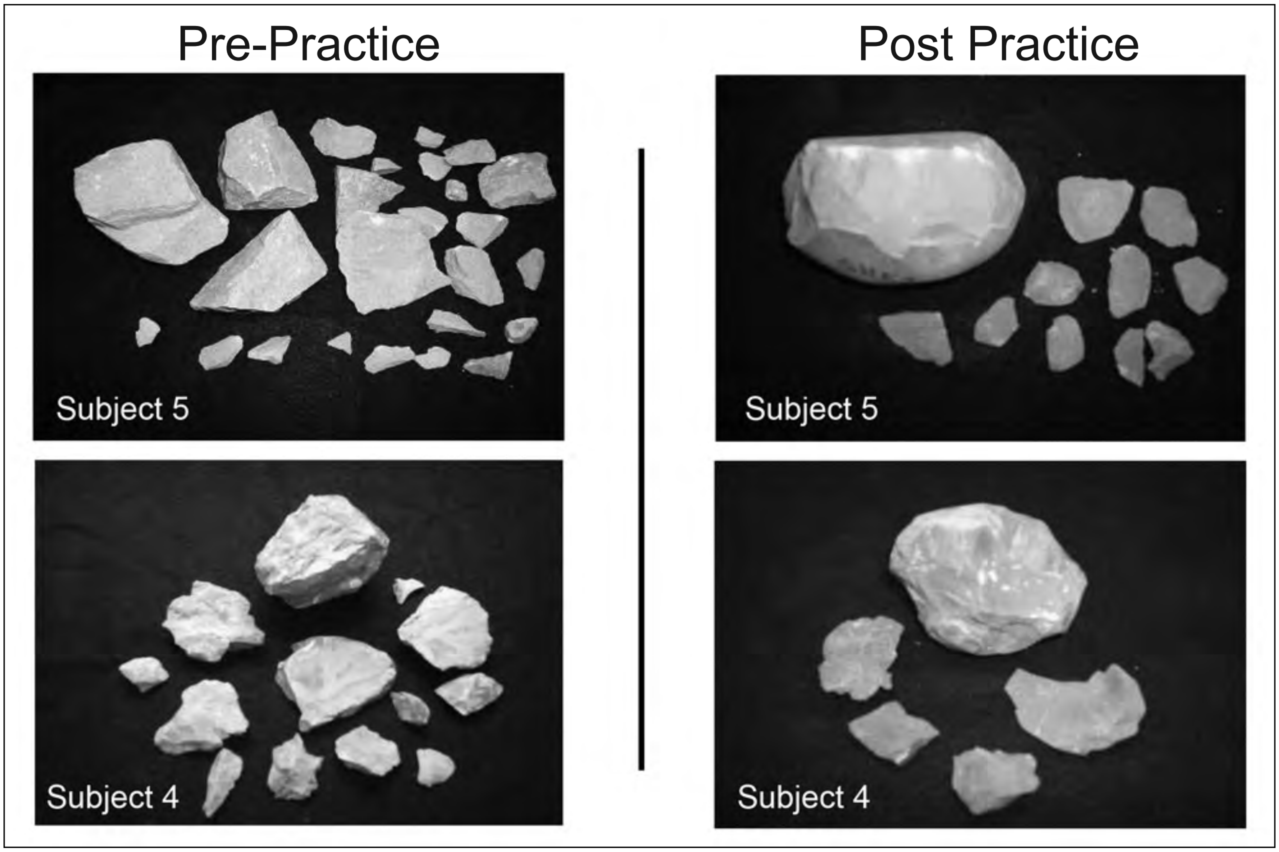

Figure 7. Representative nodules from the novice sample showing a shift to less productive but more controlled flaking following practice.

decreased significantly with the introduction of bifacial flaking by experts.

Pre-practice novices attempted a similarly uncontrolled approach to metamorphic clasts, but produced far fewer flakes per cobble ($t' = 2.14$, $df = 77.00$, $p = 0.035$). This is because the denser, water-rounded metamorphic cobbles offered fewer acute edge angles, and blows directed away from core edges typically failed to initiate fracture. As a result, the large, thick flakes typical of the pre-practice sedimentary sample were not produced, and no significant reduction in flake size was seen following practice. Post-practice novices instead adapted to the constraints of the raw material by restricting their attentions to more acute edge angles (Table 4). These projecting edges were more easily fractured, but rapidly exhausted by the short, non-invasive flake removals of novices. In fact, rounding off of edges led to early abandonment and low productivity in many post-practice metamorphic cores (Figure 7).

In all materials, post-practice novices adopted more controlled knapping techniques that minimized the amount of physical effort required to produce sharp cutting edges. This was achieved by exploiting relevant aspects of core morphology to produce small flakes and flake fragments through Hertzian fracture, reducing the force required to initiate fracture and producing proportionately more cutting edge per blow.

Brain activation

The shift to more controlled knapping techniques among novices corresponds to practice-related changes in brain activation identified through Positron Emission Tomography. Functional brain imaging results are described in greater detail elsewhere (Stout & Chaminade, 2007), but include increased activation of posterior visual association areas relating to object recognition, spatial attention and visual search following practice. These changes likely reflect increased attention to technologically relevant aspects of core morphology, including the edge configurations and angles necessary for the successful initiation of Hertzian fracture. A significant shift in the localization of activation in premotor cortex is also seen following practice, in an area relating to object prehension. This reflects changes in the handling of the core and hammerstone, likely corresponding to the learning of effective grips for the precise bimanual percussion required in conchoidal flaking. Modulation of activation in prefrontal areas relating to strategic action organization was not observed, perhaps reflecting novices' failure to exert control over core morphology and the reactive, opportunistic nature of their flaking. Ongoing imaging research with expert knappers will test this hypothesis.

Table 5. Learning stages and material correlates

Learning Stage	Experience	Technique	Potential Indications
I pre-practice novice	0 – 40 minutes	split fracture	High proportion of angular fragments; relatively thick flakes; steep EPAs (approaching 90°)
II post-practice novice	280 – 320 minutes	marginal conchoidal flaking	Proportionally more flakes and flake fragments; small, relatively short flakes; more acute (80°-85°) EPAs; rounded “prematurely” exhausted cores
III expert	multiple years	intensive bifacial reduction	Large, relatively thin and elongated flakes; increased representation of non-cortical platform flakes with optimal (75±5°) EPAs; heavily reduced bifacial cores

Archaeological implications

Results presented here document three stages of knapping skill acquisition associated with characteristic changes in assemblage composition and flake morphology (Table 5). These are: I) an initial phase of relatively uncontrolled wedging fracture, II) a rapidly achieved phase of conchoidal but minimally invasive flaking, and III) expert performance with intensive bifacial core reduction through invasive flake removals. These stages outline a modern human learning trajectory in which the basic requirements of conchoidal flaking are quickly learned, but reliable production of large flakes and controlled core reduction require more substantial investments in perceptual-motor skill acquisition. Further research with more prolonged practice periods will be required to trace in greater detail the process of expert skill acquisition, and to identify any further intermediate stages.

These observations are based on the performance of modern humans under experimental conditions, and care must be taken in applying them to the early archaeological record. For example, it is possible that greater upper body strength among Pliocene hominins would have made wedging fracture a more viable technique in a wider range of clast sizes, shapes and compositions. Conversely, differences in hand morphology (Marzke, 2005; Panger et al., 2002), manual dexterity (Maier et al., 2005), or brain organization (Stout & Chaminade, 2007) might have made the mastery of controlled Hertzian fracture more challenging. For example, hand morphology appears to be an important constraint on the knapping performance of modern bonobos (Savage-Rumbaugh & Fields, 2006). There is, however, currently no evidence to suggest similar constraints in early hominin toolmakers.

Raw material differences are another major concern, and results from the current study exemplify the influences that variable blank morphology and composition can have on artifact form and frequency (e.g. Tables 3 & 5). Previous research has similarly indicated an influence of initial cobble morphology on the occurrence of steps and hinges (Toth et al., 2006). Nevertheless, some rather robust trends were seen across raw materials, especially with respect to the increased productivity, reduction intensity and flake elongation of experts. The first two stages of skill acquisition in novices were most consistently distinguished from each other by a decrease in angular fragment production, as well as by more material-specific decreases in flake size, thickness and EPA.

Specific replication studies are required in order to properly assess individual sites (e.g. Toth et al., 2006), however it seems clear that the efficient and productive flaking reported in Late Pliocene archaeological assemblages (de la Torre, 2004; Delagnes & Roche, 2005; Ludwig & Harris, 1998; Semaw, 2000) has much more in common with expert performance than with earlier stages of skill acquisition. This is consistent with the findings of a previous study (Toth et al., 2006) showing that Pliocene archaeological assemblages from Gona, Ethiopia cluster with the products of experience modern knappers in terms of assemblage composition, core typology, flake shape, and flake elongation.

Interestingly, flakes from Gona were also found to have significantly higher EPAs than the modern experimental sample. This difference may reflect a somewhat lower level of skill in the selection and maintenance of optimal edge angles, analogous to the performance of novices in the current study. However it was not accompanied by similar deficits in flake size, elongation, or core reduction intensity. Relatively high EPAs in the Gona sample may also be related to differences in initial cobble shape and/or flake type representation arising from 1) the selection of thinner, easier-to-flake cobbles by the Gona hominins, 2) the influences of off-site flaking and selective hominin removal of useful flakes on archaeological assemblage composition, and 3) a somewhat greater incidence of bifacial flaking in the experimental sample (Toth et al., 2006). Results from the current study illustrate the influence that both clast form (e.g. angular limestone blocks) and flake type (Fig. 4) can have on EPA values.

In contrast to the experimental replication of the Gona assemblages (Toth et al., 2006), subjects in the current study were not instructed to conform to a predominantly unifacial flaking mode. In fact, the most salient difference between the modern experts in this study and Late Pliocene toolmakers was a strong preference for bifacial reduction on the part of the modern knappers. Such bifacial reduction appears to be relatively infrequent at early archaeological sites, although it is clearly present to at least some degree already in the earliest known occurrences (Semaw, 2000; Semaw et al., 2003).

It is possible that this emphasis on unifacial flaking reflects cognitive differences on the part of Pliocene toolmakers, for example in the ability to plan and execute contingent action sequences. However, the broader behavioral context of early sites, including selective raw material procurement (Stout et al., 2005) and the extensive transport of flaked materials about the landscape (Toth et al., 2006), seems to argue against this. Furthermore, the unifacial strategies of Pliocene knappers appear quite effective in producing useful flakes and reducing cores (Delagnes & Roche, 2005; Toth et al., 2006). Possible environmental, technological, and/or cognitive factors promoting unifacial reduction strategies among Pliocene toolmakers remain poorly understood and should be a focus for future research.

Despite this intriguing difference, research with modern subjects of variable skill levels strongly supports the emerging consensus that Late Pliocene hominins already displayed fairly advanced knapping skills. In fact, the general absence from the early archaeological record of anything resembling the first two stages of skill acquisition identified here is striking. While the high productivity of expert knappers in the current study does suggest that evidence of novice or inexpert knappers could easily be lost amid the products of more accomplished individuals, it is also clear that at least some such accomplished individuals were usually present in Oldowan toolmaking populations.

Many Oldowan sites do display a relatively high proportion of fragments, however this is likely due to site formation processes unrelated to knapping (Hovers, 2003), and is generally not coupled with other indicators of uncontrolled fracture (such as incomplete core reduction) seen in pre-practice novices. Wedging fracture may characterize accidental assemblages associated with percussive activity (Mercader et al., 2007; Mercader et al., 2002), and the prevalence of such activities in the Oldowan also may be underappreciated (Mora & de la Torre, 2005). Nevertheless, many Oldowan assemblages provide clear evidence of intentional flake production with controlled fracture and intensive reduction (e.g. de la Torre, 2004; Delagnes & Roche, 2005; Semaw, 2000; Semaw et al., 2003).

In contrast, modern bonobos do appear to flake stone in a relatively uncontrolled fashion analogous to the first stage of human skill acquisition described here, but with lesser hammerstone velocities than are typical of humans (Harlacker, 2006; Toth et al., 2006). This lower velocity knapping may reflect differences in hand morphology that make controlled percussion without injury to the fingers more difficult (Savage-Rumbaugh & Fields, 2006) and/or to differences in the neural regulation of visually guided prehension (Stout & Chaminade, 2007). Because behavior is a property of whole organisms, it is most likely that integrated neural and somatic factors are involved.

In any case, the outcome is that bonobo subjects did not produce the large amounts of chunky angular shatter seen in pre-practice human subjects pursuing a “brute force” approach to knapping. This is because low velocity blows directed away from core edges failed to initiate wedging fractures. For this reason, pieces actually detached tended to be very thin whole flakes with steep (~85) EPAs, each reflecting a large number of less fortuitous accompanying blows that failed to initiate fracture (Toth et al., 2006). This pattern in most closely analogous to that seen in the pre-practice metamorphic sample of the current study, in which subjects also produced a relatively high proportion of whole flakes (Table 1) which exhibited thin cross-sections and steep EPAs (Table 2). Following a relatively small amount of practice, however, these human subjects shifted to the selective exploitation of more acute core angles. This adaptation has not (yet) been seen in the products of bonobo knappers.

Comparative studies with modern apes and humans of can thus begin to define a range of knapping skill levels, from the accidental to the expert, which may be used to better understand variation within the Oldowan and even to model hypothetical “pre-Oldowan” stone technologies (Panger et al., 2002; Toth et al., 2006). For example, the rapidity with which modern humans learn to exploit the principles of conchoidal fracture suggests that a relatively prolonged (i.e. archaeologically visible) transitional phase of tool production through uncontrolled split fracture would only have been likely in the context of substantial manipulative and/or perceptual-motor differences from modern humans. Experimental studies of knapping-related prehension (Marzke, 2005) and brain activation (Stout & Chaminade, 2007) provide some further indications as to the likely nature of any such differences. At the current time, however, paleontological evidence does not support the presence of such differences in hominins ca. 2.5-3.0 Ma (Holloway et al., 2004; Marzke, 2005), and archaeological evidence for a pre-Oldowan phase of uncontrolled percussion is lacking.

Stage II (post-practice) skill perhaps provides a more likely model for unskilled knapping, either as part of a “pre-Oldowan” industry or as a dimension of variation within the Oldowan. One possible archaeological example is provided by Lokalalei 1 in Kenya, where it has been argued that relatively small flake scars on cores and a high incidence of flaking “accidents” indicate poorly developed knapping skills relative to Lokalalei 2C (Delagnes & Roche, 2005; Kibunjia, 1994). However it has also been argued that this difference arises from “subtle material flaws” (Ludwig & Harris, 1998) at Lokalalei 1, and potentially relevant differences in blank morphology have been described (Delagnes & Roche, 2005). It is, of course, quite difficult to demonstrate that low reduction intensity necessarily corresponds to a lack of ability rather than a lack of incentive, however the case may be strengthened if a broader pattern of premature core exhaustion through inefficient flaking and edge rounding may be shown, as in the current post-practice sample. Currently available descriptions and illustrations of the Lokalalei 1 cores (Delagnes & Roche, 2005; Kibunjia, 1994) do not yet clearly indicate such a pattern. As previously discussed, other early Oldowan sites clearly display knapping that is most closely analogous to fully expert, “Stage III”, modern humans.

Conclusions

The most important conclusion of the current study is that variation in knapping skill is associated with measurable, quantitative variation in assemblage composition and artifact morphology. Three stages of skill acquisition were identified, differentiated by measures of reduction intensity, debitage productivity, and relative frequency of angular fragments, as well as by flake size, morphology, and EPA. These stages reflect a rapid development from uncontrolled split fracture to deliberate, but non-invasive, conchoidal flaking and ultimately to intensive bifacial reduction.

These findings corroborate the results of a previous cross-sectional comparison of modern apes, experienced humans, and Pliocene hominins, which identified measures of reduction intensity, debitage type, flake morphology and platform angles as key indicators of knapping skill (Toth et al., 2006). The specific patterns of skill acquisition observed in this longitudinal study are also consistent with ethnographic (Roux et al., 1995; Roux & David, 2005; Stout, 2002, 2005b) and brain imaging (Stout, 2005a; Stout & Chaminade, 2007) research emphasizing the fundamental role of perceptual-motor skill acquisition in the development of knapping proficiency. Though preliminary, broad similarities between Late Pliocene archaeological assemblages and the products of modern human experts suggest substantial investments of time and effort in knapping skill acquisition already at this very early date. This, in turn, may have implications for the social context of Oldowan technology (Savage-Rumbaugh & Fields, 2006; Stout, 2005b).

These findings also support and extend the conclusions of more qualitative investigations of Oldowan knapping skill, and it is hoped that complementary application of interpretive and quantitative/experimental methods in the future will yield further insights. In this context, site-specific replication studies and the production of comparable descriptive and quantitative data from multiple sites are essential. The current study calls particular attention to the importance of studying fragments, including both typological and metric analyses, and to the value of whole flake linear dimensions, shape indices and exterior platform angles in assessing Mode I knapping skill.

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