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Late Acheulean technology and cognition at Boxgrove, UK

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ABSTRACT

The Acheulean industrial complex combines technological variability with continuity on a scale unparalleled by more recent industries. Acheulean variability includes a widely recognized increase in biface refinement from the Early to Late Acheulean, however the specific timing and technological nature of this shift remain unclear as do its behavioral, cognitive, and evolutionary implications. To investigate this topic, we examined lithic collections from the early Middle Pleistocene Acheulean site of Boxgrove for evidence of the use of platform preparation as a biface thinning technique. To aid in the identification and assessment of platform preparation, Boxgrove artifacts were compared with experimental products of Inexperienced, Novice, and Expert stone knappers. Results demonstrate the technologically efficacious use of platform preparation among the Boxgrove toolmakers ~500 thousand years ago, providing the first direct evidence of this technique in the Acheulean. The use of platform preparation in bifacial thinning increases the complexity of toolmaking action sequences and has implications for understanding the neurocognitive substrates, social transmission, and spatiotemporal distribution of Late Acheulean technology.

1. Introduction

Narratives of human evolution often emphasize the conservatism of the Acheulean industrial complex, which has been described as static, stagnant, or even monotonous (reviewed by Lycett and Gowlett, 2008; Nowell and White, 2010; Sharon et al., 2011). In the words of Desmond Clark (1994: 453–4), “The overall impression given by the Acheulian is of conformity… persisting throughout the long range of time that the complex is known to have existed.” The simple fact that artifacts spanning more than a million years across much of the Old World are attributed to a single archaeological taxon indicates a striking degree of uniformity.

This conservatism has been seen as a remarkable feature in need of special explanation, most often in terms of the limited cognitive capacities of Acheulean hominins. Mithen (1996, 1999) has argued that a lack of cumulative change in the Acheulean (as well as the Middle Paleolithic) indicates a lack of the cognitive fluidity required for technological invention. Wynn and Coolidge (2004) similarly interpret slow rates of Lower and Middle Paleolithic technological change as reflecting low levels of invention due to the limited working memory capacity of individuals. Stout (2011) speculated that limitations on individual capacities for hierarchical information processing and the social-cognitive prerequisites for apprenticeship learning may have constrained rates of Lower Paleolithic technological change. This view of Acheulean technology as inhumanly static and invariant has achieved the status of conventional wisdom in the wider academic community, and commonly informs discussions of human cognitive evolution (e.g. Corballis, 2002; Donald, 1991; Dunbar, 1996; Whiten et al., 2003).

Unsurprisingly, perceptions of Acheulean variation among Paleolithic archaeologists are more nuanced. After noting the “overall… conformity” of the Acheulean, Clark went on to clarify that “Temporal changes, however, *are* apparent” (1994: 454, emphasis original). Glynn Isaac emphasized the “extremely slow” (1989: 37) pace of early technological change but also acknowledged a clear “development of refinement… through the long time span of the Acheulean” (p. 47) and described inter-assemblage variability in the Middle Pleistocene as “very considerable” (p. 55). This mixture of stability and variability is one of the more fascinating features of Acheulean technology and, according to Sharon et al. (2011: 388), “still form[s] the bulk of present-day research activity and debate regarding the Acheulian Technocomplex.”

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One widely made distinction is between the Early and Late Acheulean. Although "crude" bifaces persist throughout the record, it is widely agreed that smaller, thinner, more regular and symmetrical forms appear in the later part of the Acheulean. Such forms are well documented after approximately 0.6–0.5 Ma (Clark, 2001; Isaac, 1989; Gilead, 1970; Gowlett, 2006). Lithic technologists (e.g. Bordaz, 1970; Bordes, 1971; Callahan, 1979; Edwards, 2001; Schick and Toth, 1993) stress the greater knapping skill and understanding implied by Late Acheulean bifaces, and it has been argued that the Early-Late Acheulean transition was of greater cognitive significance than the preceding Oldowan-Early Acheulean transition (Wynn, 1985).

Although handaxe studies have traditionally focused on plan form variation, it is widely recognized that cross-sectional thinning is one of the most distinctive and technically demanding characteristics of Late Acheuelan biface production (Bordaz, 1970; Callahan, 1979; Edwards, 2001; Schick and Toth, 1993; Winton, 2005). Experimentally, such thinning is often achieved using a soft-hammer and there is evidence that this was also the case in the early Middle Pleistocene (Roberts and Pope, 2009; Wenban-Smith, 1999) although it is possible to achieve similar results with a hard hammer (Bradley and Sampson, 1986; Pelcin, 1997). Whether using a hard or soft hammer, experimental knappers commonly prepare platforms through the small-scale chipping of striking surfaces to alter their sharpness, bevel, and placement relative to the midline (Callahan, 1979). These adjustments are thought facilitate the production of large, relatively thin flakes traveling more than halfway across the surface of the piece, which are required to thin the biface without a disproportionate decrease in breadth. Callahan (1979: 35) identifies the technique of "near perpendicular" percussion on properly prepared platforms as *the* critical technical innovation necessary to progress from producing relatively thick Abbevillian (cf. Early Acheulean) handaxes to producing refined (Late) Acheulean handaxes. This suggests to some that the invention of effective platform preparation techniques may have been a key factor in the transition from Early to Late Acheulean (Coolidge and Wynn, 2009; Schick and Toth, 1993). Systematic platform preparation associated with blade production has recently been described from the early Middle Pleistocene of South Africa (Wilkins and Chazan, 2012), but it remains to be seen whether, when, and where such techniques were applied in Acheulean biface thinning.

As a step in this direction, we examined collections from the early Middle Pleistocene Acheulean site of Boxgrove, in southern England (Fig. 1) (Pope and Roberts, 2005; Roberts and Parfitt, 1999; Roberts and Pope, 2009). The site is exceptional, not only as one of the oldest handaxe sites in Europe, but also for its pristine preservation of fauna and lithic artifacts, including copious debitage from biface production. To aid in the identification and assessment of platform preparation, the Boxgrove artifacts were compared with experimental artifacts produced by Inexperienced, Novice and Expert stone knappers. This initial study aimed to assess the presence, frequency, and efficacy of platform preparation at Boxgrove.

2. Materials and methods

2.1. Identifying and assessing platform preparation

Experimental knappers widely consider platform preparation useful, and perhaps even essential, in the production of refined bifaces with high Breadth/Thickness ratios. However, there may be other ways to produce such forms, for example if blanks are already thin prior to shaping (cf. Winton, 2005). Experimental replication

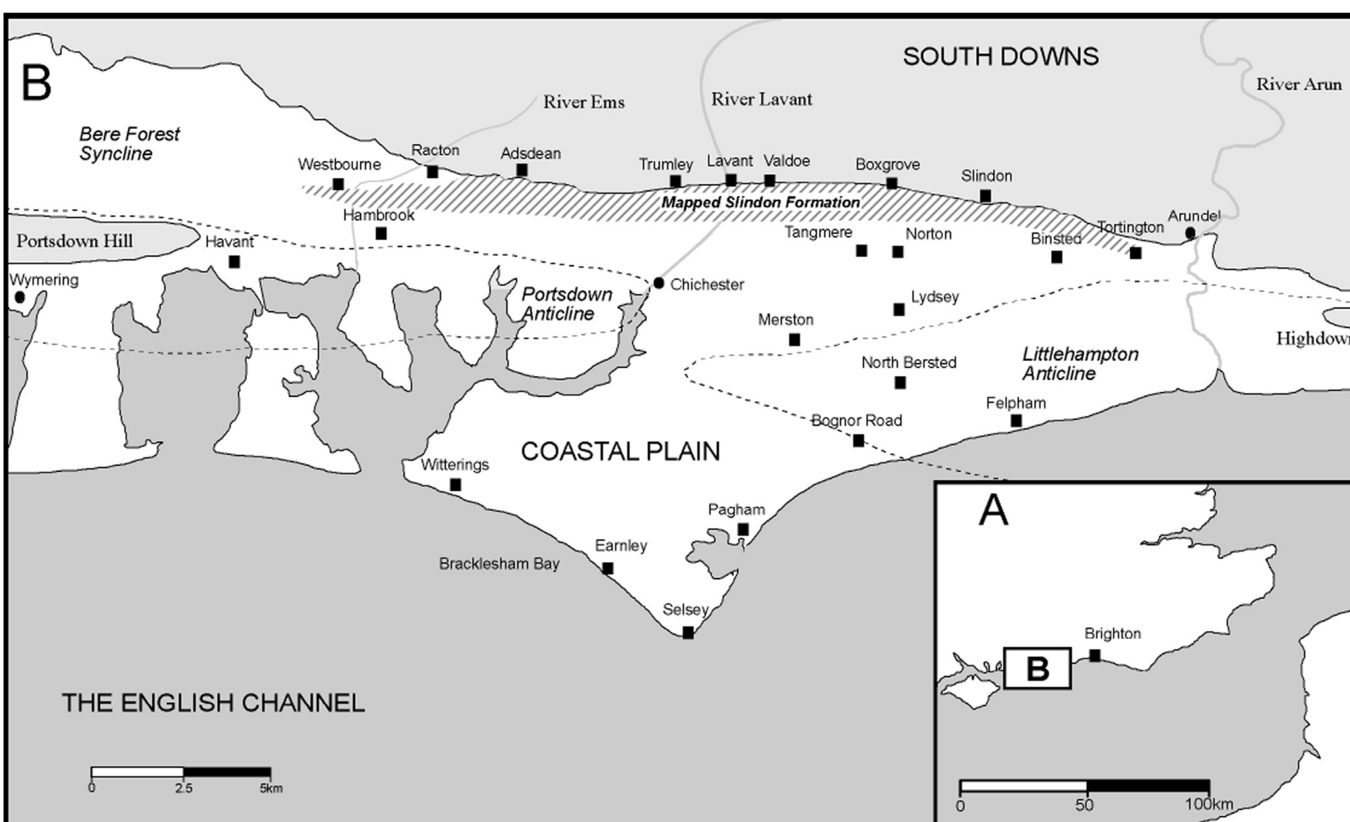

Fig. 1. Location map of the Boxgrove site showing the mapped distribution of the Slindon Formation.

cannot demonstrate that there is only one possible way to produce a given result but it can support inferences about the methods and techniques used in a given case. We thus decided to inspect the debitage of biface production at Boxgrove for direct indicators of the presence, frequency, and efficacy of platform preparation.

As most commonly used by lithic technologists, the term platform preparation refers to the systematic process of small-scale flaking and abrasion intended to shape and isolate platforms in prepared core, blade, and bifacial point technologies. In principle, however, "platform preparation" might refer to any process intended to alter core morphology in order to provide more advantageous platforms, going all the way back to the bifacial flaking and platform "rectification" reported from earliest Oldowan times (Delagnes and Roche, 2005; Stout et al., 2010). The focus here is on the small-scale flaking of striking surfaces in order to adjust edge sharpness, bevel and placement and support the "on-the-edge" marginal percussion (Bradley and Sampson, 1986) typically used to strike biface thinning flakes. The numerous small scars left by intentional preparation produce a characteristic faceting of flake platforms (Inizan et al., 1999; Wilkins and Chazan, 2012), which is not to be confused with the smaller number of flat platform "facets" that may result from capturing previous flake scars during simple bifacial flaking. We observed such faceting on experimental flakes known to have been prepared, and then interpreted similar marks on archaeological flakes from Boxgrove as also indicating platform preparation (Fig. 2). Inferences regarding the technological efficacy of preparation in facilitating biface thinning in both experimental and archaeological samples were drawn from metric comparisons of flakes with modified and unmodified platforms.

2.2. Archaeological sample

The site of Boxgrove consists of a sequence of Middle Pleistocene marine, freshwater and terrestrial sediments exposed in the former Eartham Quarry, Boxgrove, West Sussex (Fig. 3). Archaeology occurs in all the main sedimentary units in the sequence but is preserved *in situ* and in the greatest concentration within an intertidal and regressional unit, the Slindon Silts (Unit 4b) (Table 1). This unit was formed by a combination of regression and the partial blocking of the sea into a semi enclosed marine embayment (Barnes, 1980). Artifact concentrations occur on the surface of the silts in a soil horizon (Unit 4c) and in rare freshwater pond/lake deposits that are a temporal correlative of the soil horizon (Units 3c, 3/4, 4, 4u) (Holmes et al., 2010). These fine grained sediments preserve a series of ancient land surfaces with abundant faunal and lithic remains, that have been dated by correlative mammalian

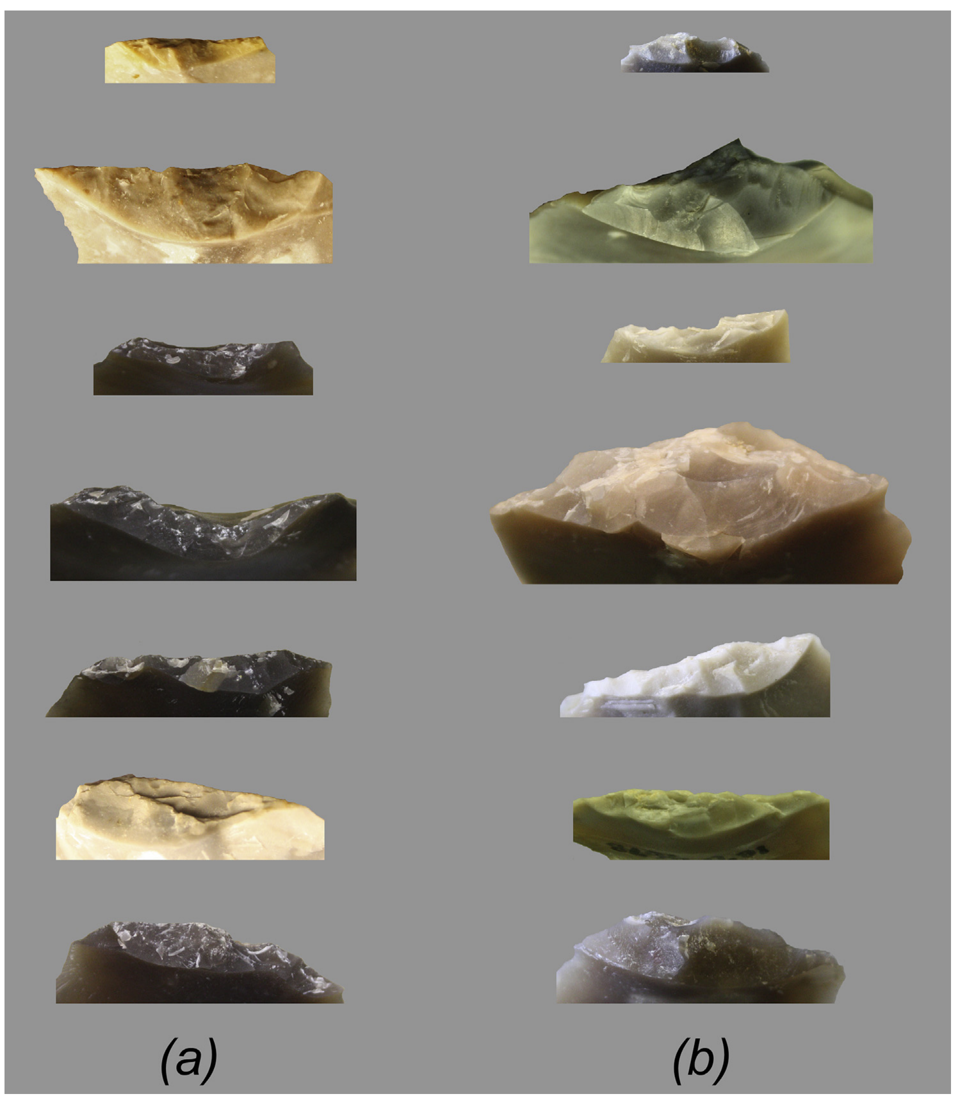

Fig. 2. Prepared platforms from the Expert (a) and Boxgrove (b) samples.

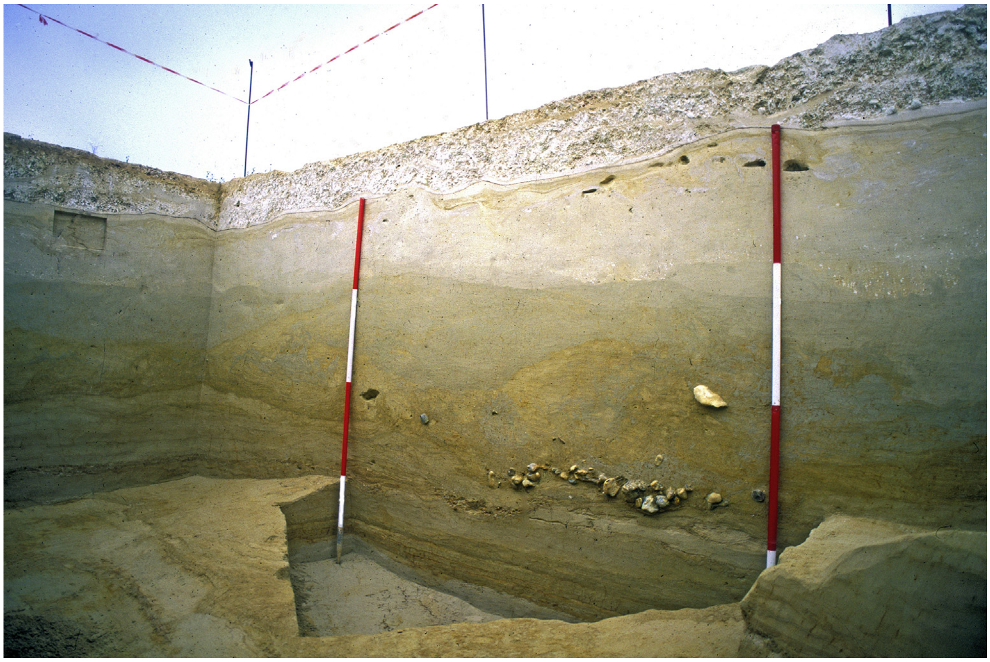

Fig. 3. The marine-freshwater-terrestrial sequence at Q1/B showing the channel and its associated infill (Unit 3c), cutting through the marine Slindon Sand (Unit 3). The channels deposits are overlain by further freshwater sediments of the waterhole, Units 4u, 4 and 5ac (Table 1). Note the presence of the mineralized organic horizon Unit 5a which completely covers the freshwater deposits at this part of the site. (Scales in 0.50 m divisions).

Table 1
Stratigraphic relationship between the standard Boxgrove sequence and that recorded at Quarry 1/B, the spring fed waterhole; the source of lithics for this analysis. Unit 4c and its chronostratigraphic correlatives are shaded in green. Unit 7, yellow, is a sedimentary unit that is in continuous formation until the burial of the cliff by mass movement deposits. Units 7 and 9 from the standard sequence are not present at Q1/B. (Not to scale).

Stage	Member	Description and Interpretation (Marine-terrestrial Boxgrove standard sequence)	Standard		Q1/B	Description and Interpretation (Marine-freshwater-terrestrial sequence)
	Eartham	Reading Beds regolith Head Gravel. Mass movement deposit		Unit 11	Unit 11	Non calcareous Head Gravel with arctic soil horizons.
	Upper Gravel	Calcareous Head. Mass movement deposit.		Unit 10	Unit 10	Calcareous Head. Mass movement deposit.
Anglian		Path gravel. Freeze thaw sorted flint gravel.		Unit 9		Residual lithics.
MIS12	Eartham Lower Gravel	Chalk pellet gravel. Colluvial, weathered and sorted chalk clasts.		Unit 8	Unit 8	Chalk pellet gravel. Dewatering structures in underlying fine grained sediments initiated. Some *in situ* & residual lithics.
		Cliff collapse.		Unit 7		
c. 478 ka		Calcareous muds/brickearth. Colluvial and waterlain silts.		Units 5b, 6	Unit 6b	As standard sequence but much thinner and restricted.
		Mineralised and compressed organic deposits. Alder/fen carr.	Unit 7	Unit 5a	Unit 5a	As standard sequence but only intact at waterhole margins.
		Soil horizon developed on top of the silts. Polder type soil.		Unit 4c	4d2, 4d3, 5ac	Spring discharge sediments with colluvial input towards the top (5ac).
					Unit 4d1	Spring discharge sediment. Intraformational calcretes. Rare lithics.
Cromerian IV	Slindon Silt	Intertidal laminated muds, laid down in a semi-enclosed marine bay.		Unit 4b	Unit 4	Massive silt from freshwater reworking of Units 4a and 4b. Heavily deformed. Lithics and butchered fauna.
MIS 13				Unit 4a	Unit 4u	Massive fine silt from freshwater reworking of Units 4a and 4b. Restricted distribution. Lithics and butchered fauna.
					Units 3/4, 3c	Freshwater channels and freshwater scoured surface, source from springs at cliff base. Vegetated landsurface developed.
	Slindon Sand	Near-shore marine sands, laid down in a semi-enclosed marine bay.	Unit 7	Unit 3	Unit 3	Nearshore marine sands with a freshwater truncated upper surface.

biostratigraphy to the last temperate stage of the Cromerian Complex, Marine Isotope Stage 13, (524–478 ka). The conformable juxtaposition of cold stage sediments overlying the temperate sediments and the presence of transitional mammal faunas, indicate that the archaeology at Boxgrove dates from the final part of the temperate stage into the ensuing Anglian Cold Stage (MIS 12). Here we report on excavated artifacts from Boxgrove Quarry 1 Area B, Project D (Q1B/D).

Rapid, quiescent site formation processes in a relatively enclosed environment produced exceptional preservation conditions, yielding pristine lithic artifacts (Fig. 4a) with minimal post-depositional movement. These lithic collections contain numerous “well-made” handaxes and have been assigned to the Acheulean industry. Typologically, ovate handaxes predominate and these include refined examples with symmetrical outlines, regular, sharp edges and Br/Th ratios > 3 (Pitts and Roberts, 1998; Roberts and Parfitt, 1999).

Previous debitage analyses indicated that soft hammers were used at the site (Wenban-Smith, 1999, 1989), and 36 bone and 3 antler hammers were recovered from the Q1/B excavations (Figs. 5 and 6). These hammers contain thousands of miniscule fragments of flint embedded within them together with larger damage such as chop and step fractures, mirroring modifications observed in experimental examples (Olsen, 1984, 1989). They occur throughout the freshwater sequence up into the base of the overlying colluvial, calcareous muds and gravels (Table 1). Two of the antler hammers are assignable on morphological criteria to the species *Cervus elaphus* and *Megaloceros dawkinsi*. The third antler hammer is represented by a partial fragment; the projected circumference and well developed pearling of which, suggest that this piece is also from a red deer antler. The bone hammers are predominantly represented by long bone shaft fragments from areas of thick cortical bone; the durable articular ends of long bones; or more rarely, dense foot bones and flaked long bone fragments from very large sized mammals. Fauna providing bones that were used as percussors include rhinoceroses, bovids and cervids.

The combination of Middle Pleistocene age, technological refinement, and exceptional preservation make Boxgrove an ideal case in which to examine evidence of platform preparation. The lithic sample considered in the current study consists of 18 handaxes and 444 whole flakes >20 mm from Q1B/D. Handaxes were purposefully selected to include the range of refinement evident at the site. The debitage sample was non-selective. The Q1B/D debitage is stored in 158 boxes containing non-consecutively numbered artifacts. We analyzed all artifacts in boxes 1–7 & 146–158 and report the whole flakes here.

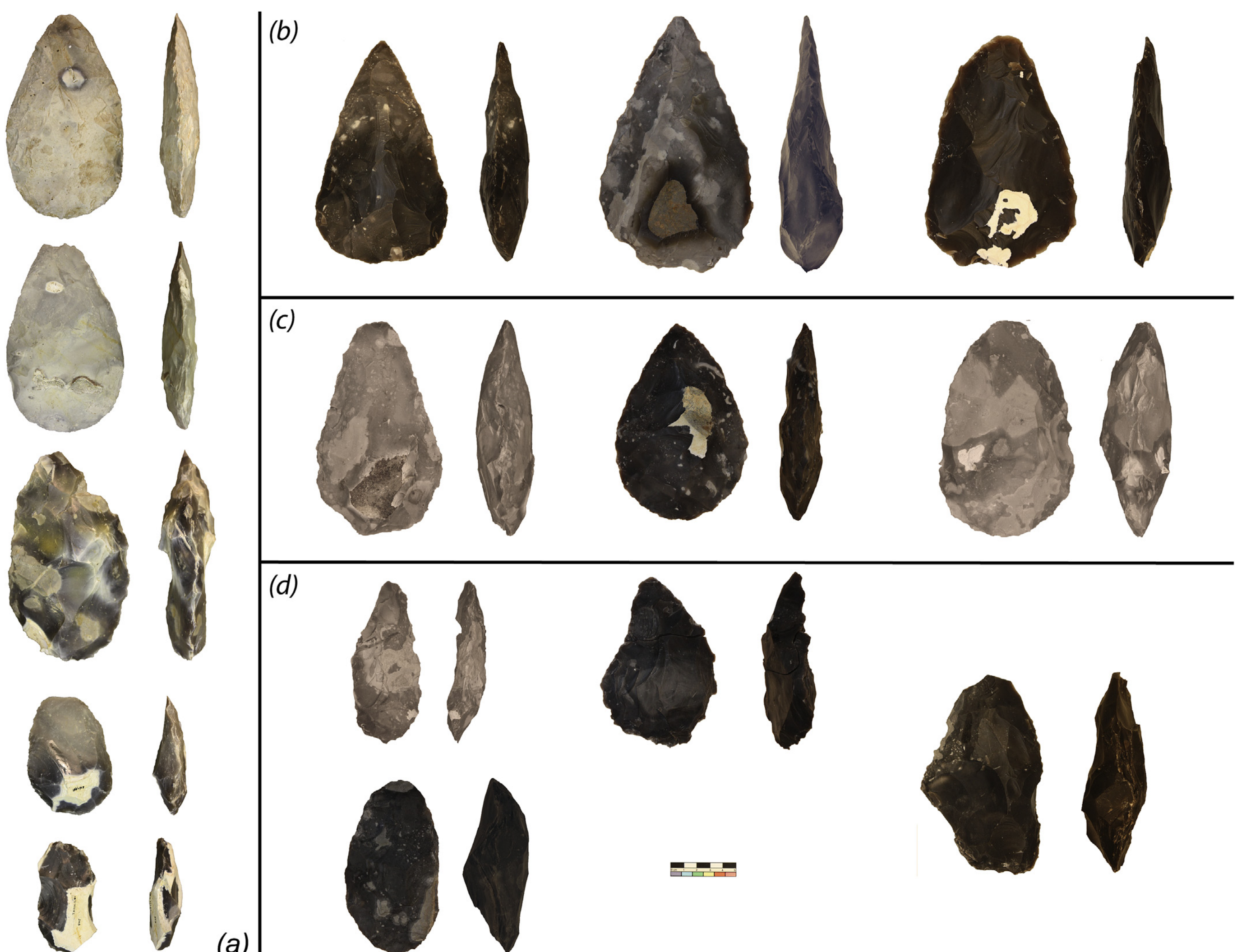

Fig. 4. Bifaces from *(a)* Boxgrove Quarry 1 Area B, Project D (Q1B/D) and *(b)* Expert, *(c)* Novice, and *(d)* Inexperienced experimental groups. All artifacts to the same scale.

Fig. 5. A soft hammer from the waterhole site Q1/B, made on a shed antler of the giant deer *Megaloceros dawkinsi*. (Scale bar in mm).

2.3. Experimental sample

The study includes 17 separate knapping experiments, each of which comprised the attempted production of an Acheulean–style handaxe by a single participant. With 3 exceptions (Table 2), all experiments were conducted with flint purchased from the Cardy of Ingham quarry in Suffolk, England. Five "Inexperienced" participants had no prior experience with stone knapping, and were among 10 such participants in a functional brain imaging (fMRI) study of handaxe making skill acquisition (Stout et al. 2011). After joining the study, they attended 16 1-h training sessions over an 8-week period, during which they were provided with tools and raw materials for practice, as well as demonstrations and interactive verbal and gestural instruction by the first author. The 1st, 8th, and 16th sessions were videotaped and products were collected for analysis. Lithic data from the 16th session are presented here. Four "Novice" participants were experimental archaeologists with several years of intermittent knapping experience at the time of participation. Novice knappers each contributed 1 or 2 experiments to the study. Two "Expert" participants were highly skilled knappers with decades of consistent and dedicated experience. The two Experts each contributed 3 experiments. Five years later, after additional practice, one of the original Novice participants (Novice 1) contributed an additional knapping experiment, which is included with the Expert group (Expert 3). For this sample, each detached piece was numbered as it was produced, allowing reconstruction of the reduction sequence. The decreasing number of participants at increasing skill levels, and compensatory increase in experiments per individual, reflects the scarcity and difficulty of recruiting skilled knappers. Expert and Novice participants provided their own knapping tools. Inexperienced participants were exposed to a range of suitable tools (hammerstones and antler billets) during training and allowed to select their preferred tools during the collected sessions. As in previous experiments (Stout and Chaminade, 2007) tool selection was treated as an aspect of skill, and tools were "standardized" with respect to participant preference and familiarity rather than size and composition.

Fig. 6. Bone hammer showing striae from periosteum removal and surface damage from use.

2.4. Lithic analyses

Handaxe attributes were recorded using the methods of Roe (1968). Because our study aimed to identify platform preparation and its possible effects on flake morphology, we focused our debitage analysis on whole flakes >20 mm in maximum dimension and displaying a feather termination. Whole flakes displaying hinge or overshot terminations were excluded. We recorded conventional linear metrics including maximum dimension, length, width, thickness, platform breadth, and platform thickness. Platform dimensions were not recorded if platform damage impacting these measures, and in such cases platforms were coded as "broken". Flakes were classified as "prepared" or "unprepared" according to the presence/absence of diagnostic modification on the platform (Fig. 2).

Statistical analyses were conducted using SPSS© 20.0, with results considered significant at $p < 0.05$. We were interested in group (Inexperienced, Novice, Expert, and Boxgrove) differences in the occurrence and effects of platform preparation. To test for variation in the frequency of platform preparation across groups, we employed Pearson's Chi-square. To test for variation in the effects of platform preparation we considered differences in the shape of prepared vs. unprepared flakes across groups. We hypothesized that platform preparation, expertise and/or their interaction would be associated with relatively thinner and more elongated flakes with relatively smaller, thinner platforms. To test these hypotheses, we calculated four flake shape indices: "elongation" (length/width), "relative thickness" (thickness/(length*width)), "relative platform area" ((platform width*platform thickness)/(flake length*flake width)), and "platform shape" (platform width/platform thickness).

We expected that these indices might scale with size. For example, small flakes might tend to be relatively thinner. This could confound analyses if samples differ in size distribution. Furthermore, handaxe production is often considered to involve three distinct stages of flaking: "roughing out", "thinning and shaping",

Table 2
Knapping samples.

		Biface weight (g)	Biface length (mm)	Biface breadth (mm)	Biface thickness (mm)	Biface refinement	# whole flakes	% hinge	% broken platforms	% (of intact) prepared
Boxgrove ($n = 18$)	Mean	**375**	**134**	**82**	**32**	**2.6**	**444**	**16.2**	**11.5**	**29.5**
	Range	80–696	80–182	46–111	19–41	1.66–3.49				
Expert 1		502	165	98	36	2.72	100	10.0	4.0	36.4
		423	168	91	27	3.37	98	4.1	0.0	36.4
		469	182	91	32	2.84	97	8.2	40.2	31.6
Expert 2		671	173	112	37	3.03	73	5.5	5.5	29.1
		924	164	117	44	2.65	86	4.7	15.1	16.4
		825	193	115	43	2.67	53	7.5	11.3	22.2
Expert 3[a,b]		706	211	115	34	3.38	124	6.5	41.1	44.4
Expert mean		**646**	**179**	**106**	**36**	**2.95**	**90**	**6.6**	**16.7**	**30.9**
Novice 1[a]		567	157	94	41	2.29	72	0.0	5.6	14.7
		448	149	101	30	3.37	142	4.2	21.8	13.7
Novice 2		793	160	102	50	2.04	85	7.1	28.2	10.9
Novice 3[b]		694	200	83	44	1.89	99	0.0	25.3	12.2
Novice 4[b]		149	91	63	26	2.42	41	0.0	22.0	9.4
Novice mean		**530**	**115**	**89**	**38**	**2.40**	**88**	**2.3**	**20.6**	**12.2**
Inexp. 1		118	114	49	23	2.13	125	28.0	7.2	10.2
Inexp. 2		409	137	83	43	1.93	127	12.6	51.2	18.3
Inexp. 3[c]		349	130	90	34	2.65	135	14.8	32.6	17.8
Inexp. 4		414	131	71	48	1.48	87	18.4	52.9	33.3
Inexp. 5		na	na	na	na	na	19	57.9	5.3	0.0
Inexp. mean		**322**	**128**	**73**	**37**	**2.05**	**99**	**26.3**	**29.8**	**15.9**

[a] Same individual at different times.
[b] Different raw material source.
[c] Broken piece conjoined for measurement.

and "finishing" (Newcomer, 1971). These stages are characterized, not only by decreasing flake size, but also by different technological objectives. This might be expected to produce systematic scaling relationships between flake size and shape. To address the issue of scaling, we performed a simple linear regression of each of our four flake shape indices against flake maximum dimension (all variables log transformed to linearize relationships). A significant scaling relationship was detected in each case so we conducted all subsequent between group comparisons using the regression standardized residuals.

To test for differences between groups we entered residual values for each whole flake shape index as the dependent variable in a two-way Analysis of Variation (ANOVA) test with group (Inexperienced, Novice, Expert, and Boxgrove) and platform preparation (present/absent) as independent, fixed factor, variables. We employed two-way ANOVA because we were interested in possible interactions between group and platform preparation, for example if platform preparation had different effects when employed by Expert vs. Novice knappers. Two-way ANOVA includes an interaction term specifically corresponding to the combined effect of the independent variables, allowing for identification of significant interactions. In the case of a significant main effect of group, we followed up with post hoc Tukey tests (which correct for multiple comparisons) for paired differences between groups in order to better understand the source of the effect.

3. Results

3.1. Handaxes

Attributes for bifacially worked pieces from the Boxgrove and experimental samples are presented in Table 2, examples are shown in Fig. 4. The Boxgrove sample, which was intentionally selected to reflect the great diversity of the collection, includes a wide range of handaxe sizes and degrees of refinement, from classic "well-made" examples to forms whose typological identification as handaxes might be questioned. Mean values for handaxe length, breath and thickness in the current, judgmental, sample are close to, but slightly above (10–15%), those reported by Iovita and McPherron (2011) for a much larger sample drawn from multiple excavation localities at Boxgrove. The mean Br/Th reported by Iovita & McPherron is 2.71 and in the current sample is 2.60, however handaxes with Br/Th > 3 are clearly present at Boxgrove (6 in this sample, others reported by Roberts and Parfitt (1999)), as are relatively thick examples (4 with Br/Th < 2.25 in this sample). Handaxe size (length) and Br/Th are correlated ($r^2 = 0.33$, $p = 0.013$) in the current sample (Fig. 7a) suggesting the presence of a geometric scaling constraint and/or a latent correlation between the size of the handaxe and the skill of the maker.

Experimental handaxes also show a wide range of variation, both between and within subject groups and even within individuals. As expected, Br/Th generally decreases from Expert to Novice to Inexperienced samples, with a similar range of values to that seen at Boxgrove. Mean Br/Th at Boxgrove (2.60) falls between the experimental Expert (2.95) and Novice (2.40) means. The relationship between handaxe length and Br/Th is not significant ($p = 0.151$) in the experimental sample, but does show clustering by skill level (Fig. 7b) along an axis of decreasing length and Br/Th from Expert to Novice to Inexperienced. This suggests that the relationship between handaxe size and Br/Th at Boxgrove may also be at least partially due skill effects.

Although we focus here on the conventional and easily quantified measure of Br/Th, it should be noted that the products of less experienced knappers (Fig. 4c,d) display numerous indicators of low skill, including irregular outline shape and failure to establish an acute bifacial edge around the piece (Schick, 1994). The piece produced by Inexperienced subject 1 probably would not be classified as a "handaxes" by many archaeologists, the piece produced Inexperienced subject 3 is broken, and Inexperienced subject 5 failed to produce any piece at all, completely reducing the nodule to flakes and fragments, including 4 large core fragments weighing between 200 and 450 g each.

3.2. Presence of platform preparation

Flakes with prepared platforms are present in substantial numbers at Boxgrove. The percentage of whole flakes with intact platforms displaying evidence of platform preparation (29.5%) at

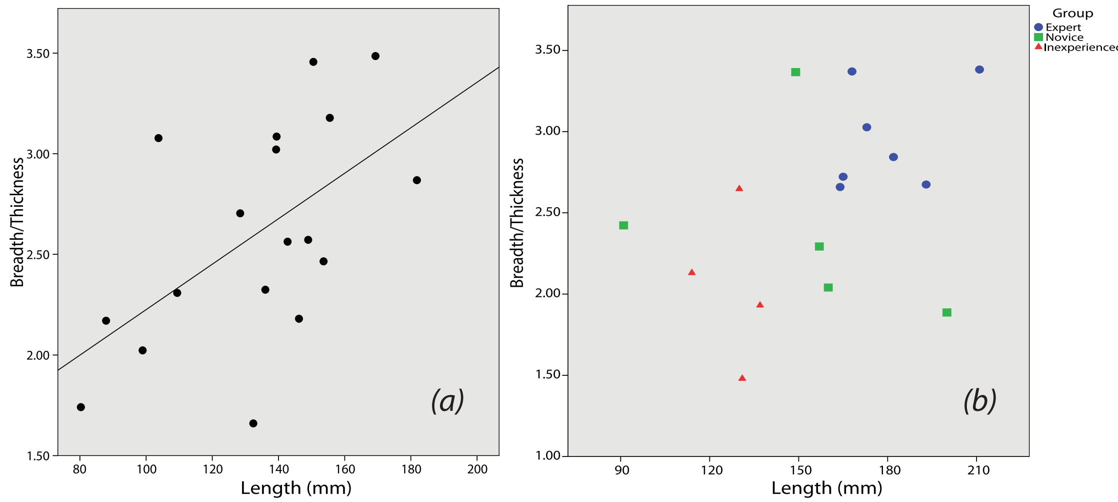

Fig. 7. Relationship between handaxe Length and Breadth/Thickness ratio in the Boxgrove *(a)* and experimental *(b)* samples.

Boxgrove very closely approximates the experimental Expert mean (30.9%) and is greater than the means for Novice (12.2%) and Inexperienced (15.9%) groups. Pearson's Chi-Square confirms that there is a significant effect of group on the frequency of prepared vs. unprepared flakes ($\chi^2 = 62.026$, df = 3, $p < 0.001$). These results confirm our primary hypothesis that platform preparation was practiced at Boxgrove, and suggest greater similarities to the knapping practices of modern experts as compared to less experienced knappers. To further investigate the latter possibility, we considered variation in the shape of prepared vs. unprepared flakes across groups.

3.3. Flake shape

As shown in Fig. 8, all four flake shape indices (elongation, relative thickness, relative platform area, and platform shape) were significantly correlated with flake size (maximum dimension). There was a fairly strong ($\beta = -0.634$, $r^2 = 0.402$) inverse relationship between flake size and relative thickness, such that larger flakes tend to be relatively thinner. Effects on other variables, though significant, were small (slopes close to 0) and explained relatively little variation ($r^2 < 0.05$).

Because we did observe significant scaling effects on all variables, we conducted all group comparisons (ANOVAs) using regression standardized residuals. Results are summarized in Table 3 and illustrated in Fig. 9. We found no significant effects of group or platform preparation on flake elongation. There was a significant effect of group on relative thickness and a significant interaction of group with platform preparation. Post hoc tests indicate that the group effect is driven by the relatively thicker flakes of Inexperienced knappers compared to Boxgrove and Experts. The interaction reflects the fact that the prepared flakes of Experts and Boxgrove are relatively thinner than unprepared flakes whereas the opposite is true of Novice and Inexperienced flakes. There was a significant effect of group on relative platform area and a significant interaction of group with platform preparation. The group effect was driven by relatively small platforms of Boxgrove compared to all other groups. The interaction reflects the fact that the prepared flakes of Experts and Boxgrove had relatively smaller platforms than unprepared flakes whereas the opposite is true of Novice and Inexperienced flakes. There was a significant effect of group on platform shape, but no effect of platform preparation or interaction. The group effect was driven by the relatively thin platforms of Boxgrove compared to all other groups.

In both cases (relative thickness, relative platform area) where a significant interaction between preparation and group was observed, Boxgrove trended in the same direction as Experts and opposite to Novice and Inexperienced groups. In no case did Boxgrove display greater similarity to Novice or Inexperienced samples than to the Expert sample. The only significant differences between the Boxgrove and Expert samples were in cases (group effects on platform area and shape) where Boxgrove differed from all experimental samples. These results indicate that knapping practices at Boxgrove were more similar to those of modern experts as compared to less experienced knappers.

4. Discussion

The current study adopted an experimental approach to assess the occurrence and technological relevance of platform preparation at the Middle Pleistocene site of Boxgrove. We found that: 1) more skilled experimental knappers employ more frequent platform preparation and produce handaxes with higher Br/Th ratios; 2) platform preparation is associated with relatively thinner flakes with smaller platforms in Expert but not Inexperienced or Novice knappers; and 3) the frequency of platform preparation and the metric differences between prepared and unprepared flakes from Boxgrove are most comparable to our modern Expert sample. These results provide empirical support for widely held views regarding the utility of platform preparation in the production of relatively thin handaxes, document skill-related variation in the use and effects of platform preparation, and demonstrate the effective use of platform preparation among the Boxgrove toolmakers ca. 500 ka.

We examined flake relative thickness because the removal of large, thin flakes is important for efficient bifacial thinning. The fact that the prepared flakes of Experts and Boxgrove are relatively thinner than unprepared flakes whereas the opposite is true of both Novice and Inexperienced flakes (Fig. 9) supports the view that effective platform preparation is a difficult technique to master and is used by skilled knappers to facilitate removal of relatively thin flakes. Our data cannot demonstrate causal relations between platform preparation and flake morphology, but do show an association of preparation with decreased relative thickness in Expert experimental and archaeological samples. We find it more parsimonious to conclude that this reflects a functional convergence than to suggest that platform preparation might be a non-functional habit independently invented and applied in similar

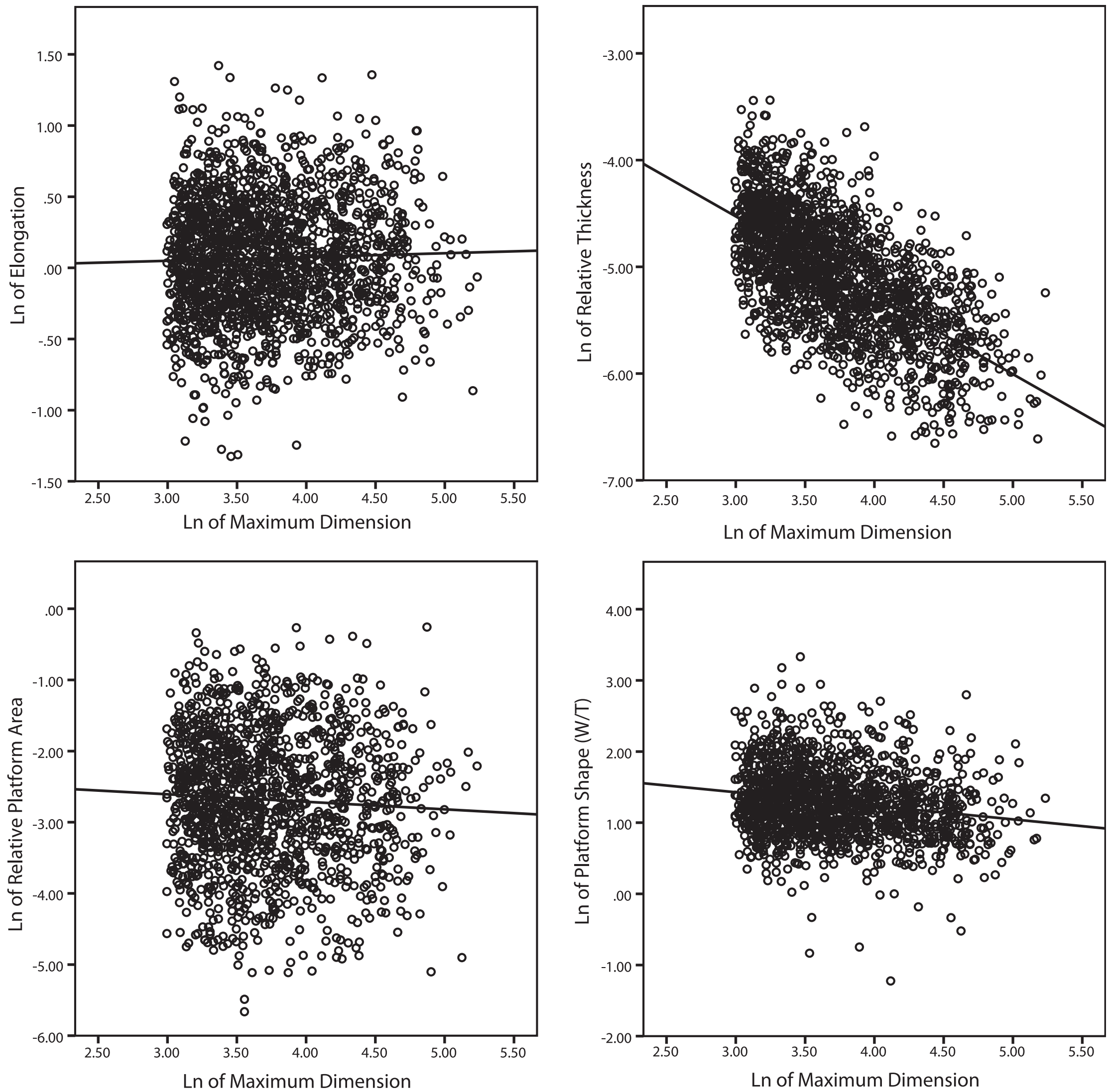

Fig. 8. Relationships between flake size (maximum dimension) and shape indices.

ways by Middle Pleistocene hominins and modern skilled (but not unskilled) knappers.

We also examined the shape and relative size of platforms because removal of flakes with small, thin platforms contributes to knappers' ability to reduce thickness while preserving breath and to produce bifaces with regular edges. We found that Boxgrove platforms were smaller and thinner than any of the experimental samples. Expert and Boxgrove samples did show a similar association of preparation with reduced platform size, again suggesting a skill-dependent functional relationship, however Boxgrove platforms were smaller overall. The small size of the Boxgrove platforms was unexpected and will require further investigation. One possibility (Bruce Bradley, pers. comm. 2013) is that the Boxgrove knappers prepared the dorsal release surface of flakes in addition to

Table 3
Results of 2-way ANOVA.

Variable	Effect	*F*	Sig.	Sig. differences from post-hoc multiple comparisons of group
Elongation	*Group*	1.765	0.152	Inexperienced > Novice
	P. Prep.	1.144	0.285	
	*Group*Prep.*	1.538	0.203	
Relative Thickness	*Group*	6.717	**<0.001**	Inexperienced > Expert & Boxgrove
	P. Prep.	2.591	0.108	
	*Group*Prep.*	4.390	**0.004**	
Relative Platform Area	*Group*	24.083	**<0.001**	Expert, Novice & Inexperienced > Boxgrove
	P. Prep.	1.245	0.265	
	*Group*Prep.*	6.663	**<0.001**	
Platform Shape (Width/Thickness)	*Group*	7.891	**<0.001**	Boxgrove > Expert, Novice & Inexperienced
	P. Prep.	3.418	0.065	
	*Group*Prep.*	1.076	0.358	

Bold indicates significant result ($p > 0.05$).

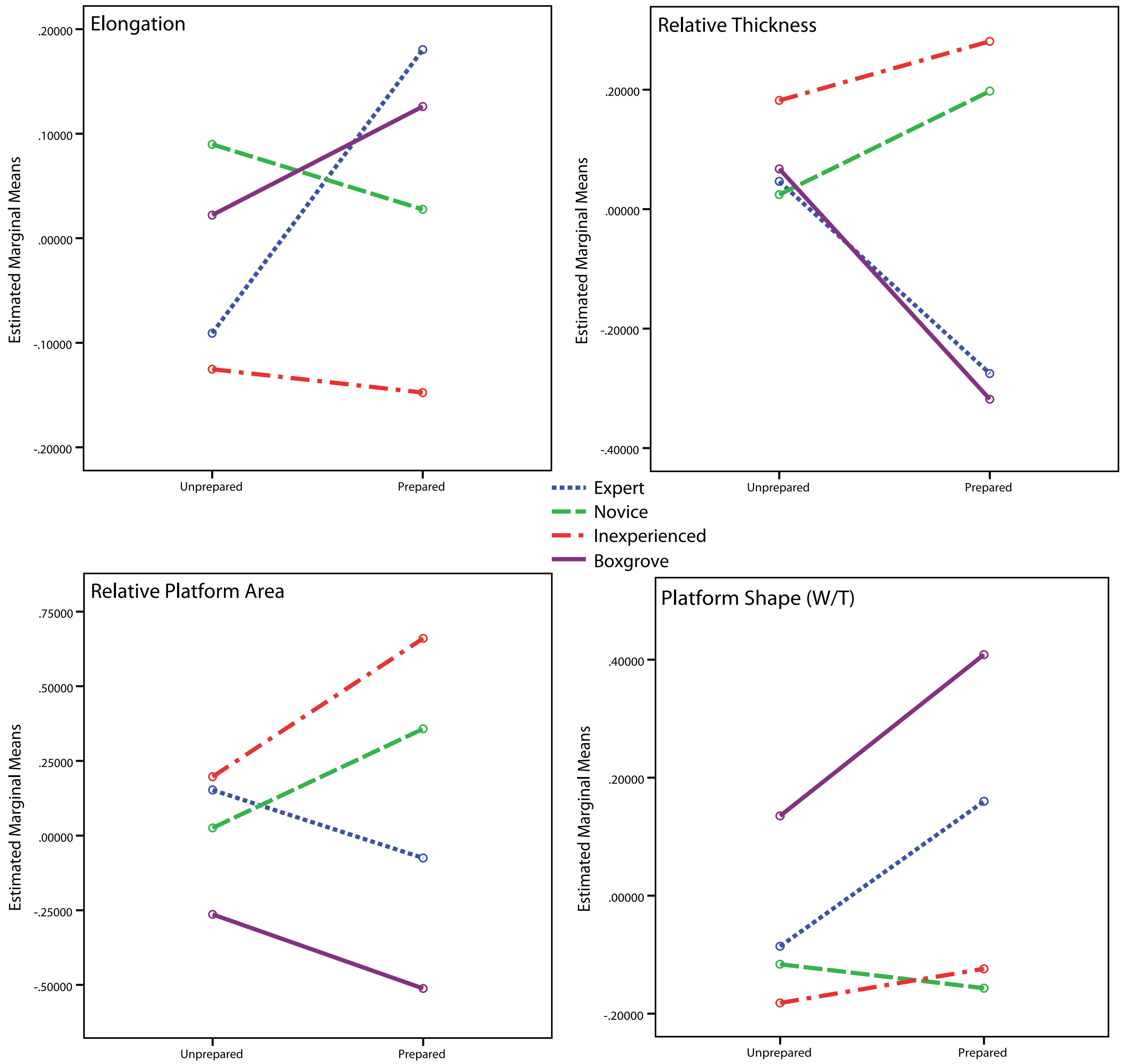

Fig. 9. Effects of group and platform type of flake shape indices.

the striking platform. Such "trimming" is sometimes done to steepen platform angles, remove overhangs and reduce the chance of accidental crushing (Whittaker, 1994). Lithic analysts and knappers more commonly associate systematic trimming with blade technology, and it was not used by any of our experimental subjects. Unfortunately we did not specifically assess the Boxgrove sample for evidence of trimming. Another possibility is that the relatively small platforms at Boxgrove reflect an over-representation of finishing and/or re-sharpening flakes. Although our residual-based analyses controlled for allometric effects of flake size, a preliminary experiment in which we recorded each flake as it was removed (Expert 3, Table 2) suggests that relative platform area may tend to decrease over the course of reduction (Fig. 10a) even after controlling for flake size (Fig. 10b). The mean relative platform area residual for the last third of this sequence was less than for the first two thirds, although this difference was not significant ($t = -1.865$, df $= 66$, $p = 0.067$) and was an order of magnitude smaller than the mean differences in residuals between Boxgrove and the experimental samples (0.05 vs. 0.40–0.60). No effect of reduction sequence on platform shape was evident (Fig. 10c).

Invasive flaking is important to biface thinning and we predicted that skilled knappers would tend to produce more elongated flakes. However, we did not find any effects of group or platform preparation on flake elongation. This suggests that the flake plan form is less important than relative thickness in achieving efficient Acheulean-style bifacial reduction.

The well-made handaxes from Boxgrove are widely considered to represent the "upper end" of Lower Paleolithic bifacial knapping skill (e.g. Iovita and McPherron, 2011). Despite the fact that poorly made, unfinished, and/or atypical bifaces are also found at the site (Fig. 4a) our debitage analyses confirm this overall impression of knapping skill at Boxgrove. Direct archaeological evidence now shows that the Boxgrove knappers employed soft hammers (Figs. 5 and 6) and prepared platforms (Fig. 2) in achieving these results. These knapping skills and methods have implications for assessing the scope and complexity of technological behavior and cognition

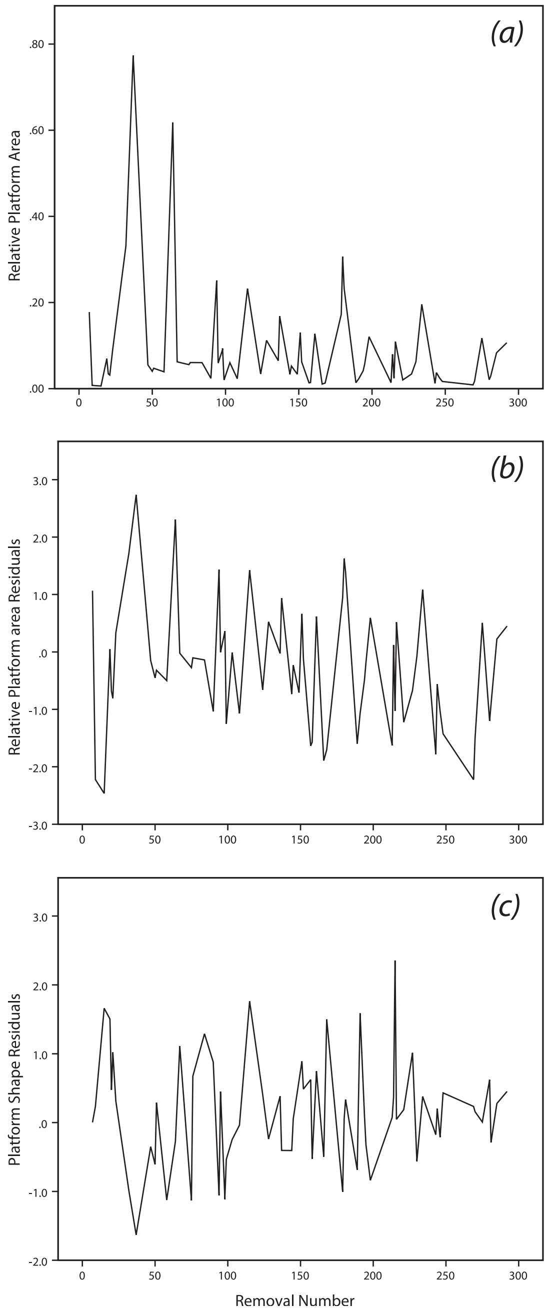

Fig. 10. Whole Flake platform size and shape by removal number for Expert 3 (Table 2).

at Boxgrove, including capacities for hierarchical behavior organization, planning, and social learning.

4.1. Hierarchical behavior organization

Human behavior is not a rigid string of concrete stimuli and responses, but is instead flexibly organized with respect to abstract goals. This organization may be described as a compositional containment hierarchy in which individual actions are assembled into increasingly abstract action "chunks." For example, "grasp knife" is a relatively concrete action that might be nested within the increasingly abstract goals of "cut bread", "make sandwich", and "prepare lunch" or incorporated into an entirely different activity such as "open package". Such hierarchical organization implies the presence of abstract goal representations and cognitive control mechanisms regulating action sequencing. These "executive functions" are commonly associated with the frontal lobes, which are thought to be organized in a posterior-to-anterior processing gradient of increasing abstraction (Badre and d'Esposito, 2009). The underlying computational nature of this cognitive abstraction remains controversial (Nee et al., 2013), but at the behavioral level it has been shown to support integration across cognitive domains (e.g. objects and space), between relational rules (e.g. A is to B as C is to D), over time (e.g. maintaining stable goals over intervening actions), and across hierarchical levels (e.g. nesting of sub-goals) (Badre and d'Esposito, 2009).

Platform preparation is a distinct sub-goal in the larger process of bifacial thinning, requiring context-dependent switching to a different set of local goals and actions that are only indirectly related to the ultimate objective. Evidence of Middle Pleistocene platform preparation presented here thus provides a direct indication of increasing hierarchical depth (Fig. 11) in hominin toolmaking. Within the frontal lobes, such hierarchical behavior regulation is supported by the inferior frontal gyri of both hemispheres (Koechlin and Jubault, 2006). The left inferior frontal gyrus, which includes Broca's Area, is best known for its contribution to processing hierarchical structure in linguistic syntax (e.g. Makuuchi et al., 2009). The right inferior frontal gyrus also contributes to language processing (Vigneau et al., 2011), but this likely reflects general contributions to cognitive control functions such as response inhibition and task-set switching (Aron et al., 2004) that are relevant to hierarchical organization across behavioral domains. In keeping with this, functional brain imaging experiments have documented increased activation of right anterior inferior frontal gyrus (*pars triangularis*) during both performance (Stout et al., 2008) and observation (Stout et al., 2011) of experimental Late Acheulean handaxe production. The stimuli used in the later study included video recordings of some of the same knapping experiments analyzed here (Expert 1, Table 1).

It has been suggested that the hierarchical processing characteristics of the inferior frontal gyrus may explain its involvement in a wide range of complex human behaviors (Fadiga et al., 2009), including language and tool use (Greenfield, 1991; Higuchi et al., 2009). Such overlapping cognitive and neural requirements cannot demonstrate the presence or absence of language in particular pre-modern hominins (Holloway, 1969) but do support the argument that adaptations for effective tool-making could have contributed to the evolution of language capacity and vice versa (Bordes, 1971; Greenfield, 1991; Holloway, 1969; Stout and Chaminade, 2012). In particular, they are consistent with an evolutionary scenario in which bilateral inferior frontal cortex underwent adaptations for stone tool-making that were exapted (Gould and Vrba, 1982) to support proto-linguistic communication and subsequently altered by secondary adaptations specific to language, especially in the left hemisphere.

4.2. Planning

The appearance of composite-tool manufacture in the Middle Paleolithic/Middle Stone Age (MP/MSA) has been considered to represent an order-of-magnitude increase in technological complexity with major implications for hominin cognition (Ambrose, 2001, 2010). Particular importance is attached to the greater diversity of raw materials, each requiring its own body of technological knowledge and skills, which must be gathered and combined at different times and places over a relatively extended period. Such complexity has been linked to enhanced planning abilities (Ambrose, 2010) and cognitive fluidity (Mithen, 1996),

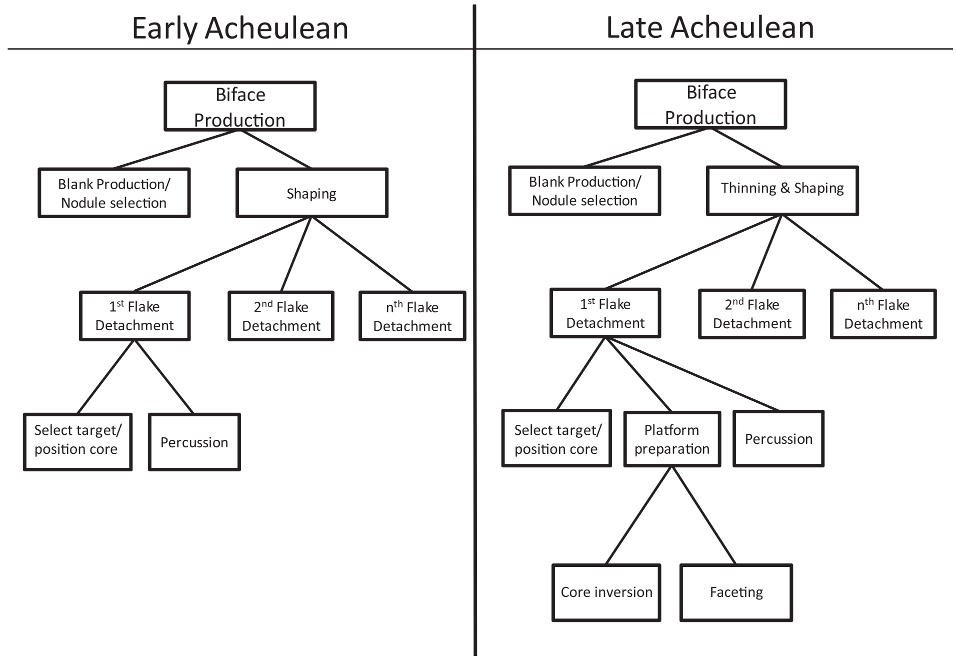

Fig. 11. Simplified goal hierarchies in Early and Late Acheulean biface production illustrating the additional hierarchical depth introduced by platform preparation. See Stout (2011) for a more complete treatment.

which may in turn be related to frontal lobe involvement in integration across time and cognitive domains.

These cognitive/behavioral analyses could be extended to consider specialized knapping tools, such as the bone and antler hammers recovered from Boxgrove, even if these materials are not incorporated into composite end-products. The production and use of such tools reflects an appreciation of interacting material properties, as well as the ability to integrate across behavioral contexts and hold multiple goals in mind during the production of a specialized tool for making other tools. Evidence from Boxgrove shows that such tools were intentionally modified for use rather than simply collected. The *C. elaphus* antler hammer was shaped through direct percussion to remove brow and bez tines and break the shaft above the bez tine. The *M. dawkinsi* antler hammer had no tines to remove at its proximal end but was flaked to produce a beveled distal end. The bone hammers often exhibit scrape marks indicating periosteum removal and/or surface preparation prior to use as a percussor. Although the production of such knapping tools is often omitted from assessments of Lower Paleolithic technological complexity (e.g. Stout, 2011), their inclusion suggests a less dramatic contrast between late Lower Paleolithic and early MP/MSA technologies. Interestingly, an unrelated analysis of knapping behavior at Boxgrove similarly identified a “surprising” ability to hold multiple goals in mind at the same time, as indicated by the deliberate setting aside of large biface thinning flakes for potential future use (Wynn and Coolidge, 2010).

4.3. Social learning

Platform preparation introduces a new sub-set of technological rules and operations into biface production. Many of these, such as the need to steepen and dull edges (Edwards, 2001; Schick, 1994) can be quite counter-intuitive for learners (Schick and Toth, 1993). This is exemplified by the Inexperienced and Novice knappers in the current study, whose prepared platform flakes were not only relatively rare (Table 1) but also relatively thicker than their unprepared flakes (Fig. 9b). This suggests that unskilled preparation was actively counterproductive and/or systematically applied in inappropriate situations. The misapplication of platform preparation by Novice knappers is striking, considering that these participants were professional archaeologists with detailed conceptual knowledge of the principles and importance of platform preparation. Clearly, this conceptual knowledge should be distinguished from the practical understanding (Pelegrin, 1990) and perceptual-motor skill (Bril et al., 2000; Roux et al., 1995; Roux and David, 2005) required for its actual application in knapping action sequences. In contrast, early Middle Pleistocene knappers at Boxgrove produced prepared platform flakes with similar metric characteristics and in similar frequencies to a sample from modern Expert knappers.

Current results support the view that, for modern humans, mastery of effective platform preparation techniques requires extended, deliberate practice. The kind of theoretical knowledge of knapping methods rapidly transmitted through observation, and/or verbal and gestural instruction (cf. Ohnuma et al., 1997) is insufficient on its own. The appearance of proficient platform preparation in the archaeological record thus implies a learning context conducive to the deliberate practice required for the individual rediscovery of such embodied skills (Stout, 2002; Nonaka et al., 2010). In modern humans, this form of learning is facilitated by cognitive capacities for complex imitation, joint attention, and pedagogy (Csibra and Gergely, 2011; Tennie et al., 2009), as well as affective dispositions favoring prosociality and enhanced self-regulation (Burkart et al., 2009; Hare and Tomasello, 2005; Stout, 2010). Increasing reliance on skill-intensive subsistence strategies appears to be a hallmark of human evolution, with wide-ranging implications for brain size, life-history and cognitive adaptations (Kaplan et al., 2000; Nowell and White, 2010). While platform preparation at Boxgrove certainly does not demonstrate “modern” social learning capacities, research focused on the learning demands of such archaeologically-visible skills is an important avenue for investigating the emergence of this distinctively human way of life.

4.4. Broader context

Wilkins and Chazan (2012) report extensive platform preparation, including both striking surface faceting and dorsal trimming, in the context of blade production in the "transitional" ESA/MSA Fauresmith Industry (Herries, 2011) at Kathu Pan, South Africa, OSL dated to 464 ± 47 ka. This is compared with a lack of platform preparation in early blade production reported from the Kapthurin Formation ($^{40}Ar/^{30}Ar$ dated to 548–500 ka [Johnson and McBrearty, 2010]) and Qesem Cave (U–Th dated to ~420–320 ka [Gopher et al., 2010]). In contrast, the spatial and temporal distribution of platform preparation in the preceding Acheulean remains virtually unknown.

Previous discussions of Late Acheulean technological complexity correctly emphasize the diversity of core preparation methods used to produce standardized Large Flake Blanks (LFBs) (e.g. Clark, 2001; Sharon, 2009). These Late Acheulean core preparation methods may reflect continuity with emerging MSA prepared core technologies (Clark, 2001; Tryon et al., 2005). In many cases, production of standardized LFBs obviated the need for substantial secondary thinning and shaping (Sharon, 2008) and platform faceting may not have been a relevant technique. However, extensively retouched bifaces are known from LFB Acheulean assemblages at sites like Isenya (Roche et al., 1988) and Middle Awash (Heinzelin et al., 2003). Recently, Beyene, et al. (2013) described refined handaxes at Konso, Ethiopia (~0.85 Ma by combined $^{40}Ar/^{30}Ar$ and paleomagnetism) that display "shallow and invasive" flake scars thought to imply "some degree of soft hammer use." The early occurrence of soft hammer, marginal percussion, and platform preparation techniques in the African Acheulean needs to be further investigated.

The LFB Acheulean is present in South (Pappu et al., 2011) and West (Bar-Yosef and Belmaker, 2011) Asia from >1.0 Ma, and is roughly comparable to African Acheulean assemblages of similar ages (Clark, 1994). The LFB Acheulean is represented in southern Europe somewhat later, likely after ~600 ka (Jiménez-Arenas et al., 2011), and again shows similarities to contemporaneous African assemblages (Santonja and Pérez-González, 2010), possibly indicating a Middle Pleistocene Out of Africa dispersal event (Hublin, 2009). In contrast, bifaces in northern European and later (<0.7 Ma) Levantine (Sharon, 2008) assemblages were produced almost exclusively from flint nodules, a process that implies substantial thinning and shaping. It has been argued that the use of flint nodules in these areas and time periods reflects hominin technological choice, rather than simple patterns of raw material availability (Sharon, 2008). The invention or diffusion of platform preparation and/or soft hammer technique may have been an important factor influencing this choice. In particular, these techniques might make the production of efficient (cf. Machin et al., 2007) tools from small, relatively thick nodules of flint more viable, altering the relative utility of different raw materials and biface production methods. This could have implications for the adoption and spread of bifacial technologies in northern Europe and elsewhere, including East Asia.

Handaxes are present east of the "Movius Line" from ~800 ka (Yamei et al., 2000), but remain rare and are relatively thick and "crudely" flaked compared to Late Acheulean examples from the West (Lycett and Bae, 2010). It has been suggested that this may reflect an interruption in the transmission of Acheulean technology during hominin dispersal eastward (Schick, 1994) and that relatively crude bifaces east of the Movius Line are examples of independent technological convergence (Lycett and Norton, 2010). Our results illustrate the fact that Late Acheulean biface thinning generally, and platform preparation specifically, are difficult and counter-intuitive skills to master. As such, they would be more vulnerable to loss through cultural drift in small populations (Henrich, 2004) as well as less likely to be independently reinvented compared to more basic (cf. Early Acheulean) bifacial shaping. This is consistent with a demographic model of technological variation east and west of the Movius Line (Lycett and Norton, 2010), which proposes that the scarcity and relatively crude morphology of East Asian handaxes is symptomatic of lower effective population sizes.

Interest in demographic explanations of technological change has been stimulated by increasing appreciation for the diversity and antiquity of cultural innovations in the MSA/MP (e.g. McBrearty and Brooks, 2000, d'Errico and Stringer, 2011), and formal modeling has provided in-principle support for the argument that slow and discontinuous technological change can be explained as an effect of low population densities without stipulating pre-modern cognitive limitations (Powell et al., 2009). Nowell and White (2010) seek to extend this perspective back in time, arguing that Acheulean technological variation is underappreciated and displays a similar pattern of short-lived and/or geographically restricted innovation to that seen in the MSA/MP. Proposed examples include continental-scale differences in handaxe shape (Lycett and Gowlett, 2008; Wynn and Tierson, 1990), the presence/absence of cleavers (White, 2006), variation in LFB production methods (Clark, 2001; Sharon, 2009), and the sporadic appearance of technological features such as tranchet removals and twisted edges. Platform preparation techniques and the production and use of soft hammers could be added to this list. Nowell and White acknowledge "a million-year stasis in the overarching technological system" (p. 71) but point out that "given the low level of technology… there are only so many modifications that could be made [and] many of these were at some point in time" (p. 73). Stout (2011) similarly notes that simplicity constrains variation and suggests that the broad trend toward increasing rates of technological change throughout the Paleolithic (e.g. Isaac, 1989) may largely reflect the autocatalytic dynamics of increasing technological complexity apart from any more particular inflections caused by extrinsic environmental, social or cognitive changes. Evidence of Acheulean platform preparation is interesting, not simply as one more technological variant, but as a technical innovation that affords greater control over the lithic medium, stimulating further innovation and potential reapplication in other contexts, such as prepared core and blade technologies.

Although it is difficult to trace connections between biological and technological change in hominin evolution the early Middle Pleistocene (~780–400 ka) stands out as a tumultuous time for both. This period encompasses some of the fastest increases in encephalization of the past 2 million years (Ruff et al., 1997), the appearance of a new hominin species (*Homo heidelbergensis* [Stringer, 2012]) with cranial capacities overlapping *Homo sapiens*, and a substantial range expansion and niche diversification (e.g. Parfitt et al., 2010) including persistence in Eurasia through entire ice age cycles (Stewart and Stringer, 2012). Globally, the Early-to-Middle Pleistocene climatic transition ushered in a period of high amplitude glacial variability (Clark et al., 2006), with likely impacts on evolving hominin populations throughout Africa and Eurasia (Potts, 1998). Technologically, the early Middle Pleistocene witnessed the spread of Late Acheulean bifacial thinning and shaping techniques, including platform preparation and soft hammers, as well as the advent of prepared core technology (Tryon et al., 2005), blade production (Johnson and McBrearty, 2010), spear hunting (Thieme, 1997), and hafting (Wilkins et al., 2012). The relative timing and interaction of these biological, climatic, and cultural events warrants further investigation.

5. Conclusions

Late Acheulean toolmakers at Boxgrove ~500 ka employed platform preparation in a manner closely analogous to modern

Expert knappers. Such platform preparation increases the hierarchical depth of tool-making action sequences, and thus helps define the minimum demonstrated cognitive capacities of Late Acheulean hominins. Functional brain imaging experiments show that hierarchical behavior organization in general, and Late Acheulean knapping in particular, are supported by the cognitive control functions of the inferior frontal gyrus, a brain region also involved in processing the hierarchical structure of linguistic syntax. Inexperienced and Novice experimental knappers do not employ platform preparation in an effective manner, despite conceptual familiarity with the technique. The archaeological occurrence of effective platform preparation thus implies time invested in deliberate practice to acquire procedural skill, together with the self-control and social context that make such practice possible. The learning difficulties associated with platform preparation would have represented an impediment to the cultural transmission of Late Acheulean bifacial thinning technology and may help to explain aspects of regional patterning in the Middle Pleistocene archaeological record. The documentation of both platform preparation and soft hammer production and use at Boxgrove adds to the known technological complexity and spatiotemporal variability of the Acheulean, and to the emerging picture of the early Middle Pleistocene as a critical period in hominin biocultural evolution.

Acknowledgments

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