Journal of Archaeological Science 36 (2009) 2039–2047

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Experimental use and quantitative performance analysis of triangular flakes (Levallois points) used as arrowheads

Matthew L. Sisk [a,*], John J. Shea [b]

[a] Interdepartmental Doctoral Program in Anthropological Sciences, Stony Brook University, SBS-S501, Stony Brook, NY 11794-4364, USA
[b] Department of Anthropology, Stony Brook University, SBS-S501, Stony Brook, NY 11794-4364, USA

ARTICLE INFO

Article history:
Received 29 March 2009
Received in revised form
11 May 2009
Accepted 21 May 2009

Keywords:
Experimental archaeology
Levallois points
Paleolithic
Arrowheads
Projectile technology

ABSTRACT

The invention and widespread use of projectile weaponry is a characteristic presumed to exist only with *Homo sapiens*. However, as finds of wooden material during the early development of projectile weapons are extremely rare, this remains a contentious topic. Recent work has proposed a series of ballistically-significant morphological characteristics of stone points that yield information about their potential use. Here we report on initial experimental approaches to quantifying the performance of relatively simple stone points as arrow armatures. Two experimental trials were performed using a series of 51 Levallois points. The first, against a uniform density target, was designed to give an overall indication of performance. The second, against a simulated animal carcass, demonstrated the durability of these points. The results of this study suggest that small Levallois points could have functioned as arrowheads, albeit ones likely to break after limited use. They also suggest that these points' penetrating power is strongly controlled by their morphometric characteristics, most notably their perimeter. This latter finding refines a method for assessing hypothetical Paleolithic stone points on the basis of tip cross-sectional area previously proposed by others.

1. Introduction

Projectile technology, which confers on its users the ability to kill at a distance, appears to have been one of the crucial behavioral innovations associated with *Homo sapiens* populations around 40–50 Kya. Earlier hominins devised heavy throwing spears and other weapons that might have been "projectiles", but light weapons that inflict lethal puncture wounds from tens of meters distant (i.e., bows and arrows, spearthrowers and darts) are uniquely associated with our species (Shea, 2006, 2009). The use of projectile weapons in subsistence is frequently numbered among the defining characteristics of the "Middle to Upper Paleolithic Transition" (Dennell, 1983; Mellars, 1973; White, 1982), the "transition to cultural adaptations" (Binford, 1989), the "Human Revolution" (Mellars, 2007; Mellars and Stringer, 1989), the "Upper Paleolithic Revolution" (Bar-Yosef, 2002), and as a characteristic of "behavioral modernity"/"modern human behavior" (Henshilwood and Marean, 2003; Stiner, 1993). Historically, prehistorians have treated the behavioral changes that occurred during this period as part of a single process, the "origins of modern human behavior"; yet, it is becoming increasingly clear that the timing and synchronicity of behavioral changes in the European Middle to Upper Paleolithic Transition are not replicated in Sub-Saharan Africa (McBrearty, 2007; McBrearty and Brooks, 2000) in Australasia (Habgood and Franklin, 2008; O'Connell and Allen, 2007; Stern, 2009), or in East Asia (Gao and Norton, 2002). Though some still envision this process as an integrated saltational change, a "great leap forward" (Klein, 2008), other archaeologists are increasingly heeding Henshilwood and Marean's (2003) call to investigate the sources of strategic variability in the particular component behaviors that define "behavioral modernity" (Kuhn and Stiner, 2006; Shea, 2009; Stiner and Kuhn, 2006).

Studies of weapon technology, prey choice, and hunting strategies suggest that the inception of projectile weaponry should be correlated with shifts in foraging strategies leaving a signature in the zooarchaeological record (Churchill, 1993). Yet, evidence for a marked shift in hunting strategies across at 40–50 Kya plausibly referable to projectile weapon usage remains elusive, or at best controversial (Chase, 1989; Kaufman, 2002; Shea, 2007; Stiner and Kuhn, 2006). Stiner et al. (1999) and others (Klein, 2008) have documented a shift towards increased predation on small and sedentary species during the Upper Paleolithic, but most evidence for this trend occurs long after 40 Kya, and it is not at all clear that the procurement of the relevant species (i.e., birds, lagomorphs,

* Corresponding author.
E-mail addresses: Matthew.Sisk@sunysb.edu (M.L. Sisk), John.Shea@sunysb.edu (J.J. Shea).

0305-4403/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2009.05.023

tortoises, shellfish) necessarily involved projectile weaponry. Due to taphonomic factors, efforts to investigate the origins of projectile technology in periods prior to 40–50 Kya have focused on the antiquity of stone projectile armatures (Shea, 2006, 2009). In the past, most of such investigations involved gross morphological comparisons between pointed stone artifacts from European and North African "Middle Paleolithic" and Sub-saharan African "Middle Stone Age" contexts on the one hand and more recent prehistoric and ethnohistoric stone points on the other (Kuhn and Stiner, 2001; Shea, 1997). Wear pattern interpretation has been a second significant avenue of research (Lombard, 2005; Shea, 1988). Recent investigations of early projectile points have involved detailed statistical comparisons of these artifacts ballistically-significant morphological characteristics, i.e., cross-sectional area, tip convergence angle, mass (Brooks et al., 2006; Shea, 2006; Waweru, 2007). One obstacle to such comparisons is that there are only small numbers of hafted stone projectile points of "known" (or at least credibly-documented) function preserved in the world's ethnographic museums. These stone-tipped projectile weapons are of relatively recent vintage. Basing the recognition criteria for earlier projectiles on these artifacts alone could result in an overly restrictive standard. These comparative collections are mostly from North American contexts. The potential stylistic and morphological differences between North American arrowheads and dart tips and Old World Paleolithic stone tools may introduce an additional source of error, or at least a problem for straightforwardly deriving middle-range interpretive principles.

A further noteworthy problem is that the statistical characteristics of Paleolithic archaeological samples of stone "points" are often skewed by the inclusion of tools far too large to be plausible weapon armatures (shown through ethnographic comparisons) together with much smaller artifacts (Shea, 2009). This problem originates in measurement-free approaches to stone tool typology in Paleolithic archaeology whose reformation lie beyond the scope of this paper.

Archaeologists interested in prehistoric projectile technology have long had recourse to experimental archaeology (Cheshier and Kelly, 2006; Flenniken and Raymond, 1986; Odell and Cowan, 1986). Controlled experiments testing the projectile capabilities of replicas of prehistoric stone and bone artifacts have focused on artifact-types from Upper Paleolithic/Later Stone Age, Mesolithic/Epipaleolithic, or Neolithic periods (Knecht, 1997). A far smaller, albeit growing, number of experiments have focused on the possible use of Middle Paleolithic/Middle Stone Age tools as either tips for thrusting spears (Shea et al., 2001, 2002) or as projectile points (Lombard and Pargeter, 2008; Plisson and Beyries, 1998). This paper presents the results of controlled experiments using a series of small, lightly-retouched and unretouched triangular flakes of the sort found in nearly all Middle Paleolithic and Middle Stone Age industries in experiments simulating their use as arrowheads. In terms of traditional European Paleolithic systematics, these artifacts would be classified as "Levallois points (Bordes, 1961)".

Arrow points are found in a wide variety of forms throughout the archaeological record. Hughes (1998) found that the most effective shape for a stone projectile point was one with a thin, elliptical cross-section. Though a smaller point is uniformly better for penetration, the cross-sectional area of the point must also be larger than that of the shaft to which it is attached. Thin lithic points, however, are easily fractured. The optimum shape of a point for durability is thus much different. A thicker-based, more conical, point is better at resisting compressive forces and thus impact fracture (Hughes, 1998). Thus, there exists a trade off between thinness for penetration and thickness for durability. A number of factors combine to make the optimum shape less common than would be expected in the archaeological and ethnographic record. Some of these include raw material quality and size, cultural variability, and the utility of barbs and serrations in causing increased hemorrhage.

Odell and Cowan (1986) found that although heavily-retouched pieces function well as arrowheads and dart tips, there is no significant difference in penetration depth between these pieces and unretouched flakes with a roughly triangular shape. This would seem to indicate a possibility that throughout prehistory relatively simple unretouched triangular flakes could have been used as effective projectile points. How the use of such simple points might relate to the development of more formal, heavily-retouched, and standardized projectile point morphotypes remains unknown. Analyzing less formal tools may shed light on the energetic costs of creating such formal points compared to the "least effort" strategy of hafting unmodified flakes as projectile points.

This paper documents a series of experiments testing the functionality of simple triangular points; lithic points that morphologically conform to the basic shape of a projectile point while not requiring heavy amounts of retouch. The experimental collection consists of points reduced by the Levallois prepared core technique. The choice of these points was inspired in part by an earlier study investigating the effectiveness of Levallois points from Levantine Middle Paleolithic contexts as hafted stone spear points (i.e., as tips of thrusting spears) (Shea et al., 2002, 2001). It was also prompted by lingering questions about a Levallois point deeply embedded in the vertebrae of an equid at the Syrian site of Umm el Tlel (Boëda et al., 1999). Boëda and colleagues presented this find as evidence of hunting, but they concluded that the issue of whether or not it was a projectile point could not be determined. This experiment will, in part, shed light on the plausibility of viewing the Umm el Tlel point as an arrowhead.

The main goal of the paper, in particular, is to test the effectiveness of simple pointed stone artifacts (in this case Levallois points) as projectile points. Using these data, we also endeavor to test the various metric criteria that have been proposed as proxy measures for projectile use particularly the interplay of tip cross-sectional area and tip cross-sectional perimeter (Hughes, 1998; Shea, 2006; Shott, 1997; Thomas, 1986). To this end we separate penetration (in this experiment our primary measure of effectiveness) and durability by firing the replicated points at both a uniform target and a simulated animal carcass.

2. Materials and methods

This experiment used fifty-one triangular flakes made of Cenomanian and Turonian (Late Cretaceous) flint knapped by a professional flintknapper, Mr. Dody Ben-Amy of Kazrin, Israel. In a Bordes' typology, all of these points could all be classified as either Levallois Points or Retouched Levallois Points. The points ranged in overall length from 30.99 mm to 75.95 mm and in mass from 2.9 g to 24.5 g. Maximum thickness before hafting ranged from 4.2 mm to 11.2 mm and maximum width from 17.5 mm to 36.9 mm. Metric data for all points can be found in Table 1. Most points ($n = 42$) had light to semi-abrupt retouch on their distal tips. This retouch was very restricted in its extent and functioned only as part of final shaping, not resharpening (Fig. 1). Nearly all of these points were below the size estimate for the point fragment recovered from the vertebrae at Umm el Tlel (Boëda et al., 1999: 397). All of the points fall within the lower range of excavated Levantine Levallois points. Fig. 2 shows that while these experimental points are within the variation of a larger archaeological sample of Levallois points, they are most similar to the smallest of such points, and at the low end of ethnographic dart and arrow points (Shott, 1997; Thomas, 1978). We chose to use points that fall within the overlap (in tip cross-sectional area) of both ethnographic dart and arrow tips and excavated Levallois points

Table 1
Morphological and penetration data for the experimental sample.

Point #	Mass (g)	Length (mm)	Max. width (mm)	Max. thickness (mm)	Retouch	Cross-sectional area (mm^2)	Cross-sectional perimeter (mm) (Hughes, 1998)	Cross-sectional perimeter (mm) (Sisk)	Forshaft size	Penetration depth (cm): Trial 1	Pentration ratio (Trial 1)	Maximum penetration depth (cm): Trial 2
1	3.7	45.32	19.9	5.8	No	57.71	41.46	62.32	A	10.0	2.21	8.0
2	9.0	61.44	22.7	5.9	Yes	66.97	46.91	70.58	A	8.0	1.30	–
3	7.3	45.56	23.1	7.0	No	80.85	48.27	72.33	A	6.5	1.43	5.0
4	7.4	48.90	33.7	5.3	Yes	89.31	68.23	102.92	A	5.5	1.12	2.0
5	7.8	56.09	26.4	5.0	Yes	66.00	53.74	81.12	A	10.5	1.87	10.0
6	4.1	40.39	31.1	4.2	No	65.31	62.76	94.86	A	5.5	1.36	0.0
7	10.5	49.91	29.8	7.6	Yes	113.24	61.51	92.28	A	7.5	1.50	0.0
8	2.9	30.99	24.7	4.7	No	58.05	50.29	75.97	A	0.0	–	–
9	8.6	54.02	27.8	5.6	Yes	77.84	56.72	85.50	A	9.5	1.76	8.5
10	3.3	36.26	21.3	5.0	No	53.25	43.76	66.03	A	8.0	2.21	8.0
11	7.7	52.00	24.0	7.2	Yes	86.40	50.11	75.07	A	6.5	1.25	6.5
12	3.3	34.77	17.5	6.0	No	52.50	37.00	55.45	A	9.5	2.73	10.0
13	4.3	38.29	24.3	6.3	No	76.55	50.21	75.48	A	7.5	1.96	6.0
14	11.3	59.81	27.7	8.2	Yes	113.57	57.78	86.44	A	7.5	1.25	–
15	7.0	52.17	26.5	6.8	Yes	90.10	54.72	82.19	A	6.5	1.25	0.0
16	9.2	53.23	27.4	7.3	Yes	100.01	56.71	85.08	A	5.5	1.03	8.0
17	5.9	45.40	29.5	5.1	Yes	75.23	59.88	90.36	A	6.5	1.43	7.0
18	16.1	75.95	29.9	8.9	Yes	133.06	62.39	93.25	B	10.0	1.32	0.0
19	17.1	56.30	31.3	10.0	Yes	156.50	65.72	97.97	B	7.0	1.24	0.0
20	12.5	62.33	36.9	6.6	Yes	121.77	74.97	112.86	B	0.0	0.00	0.0
21	13.6	65.14	27.2	9.0	Yes	122.40	57.30	85.45	B	7.0	1.07	0.0
22	9.5	52.82	34.1	5.8	Yes	98.89	69.18	104.27	B	10.0	1.89	5.0
23	11.1	61.31	28.9	6.7	Yes	96.82	59.33	89.21	B	8.0	1.30	0.0
24	10.7	49.16	31.6	8.6	Yes	135.88	65.50	98.06	B	5.0	1.02	8.0
25	13.8	65.34	30.1	7.9	Yes	118.90	62.24	93.31	B	4.0	0.61	8.0
26	15.5	63.54	28.9	10.1	Yes	145.95	61.23	91.07	B	7.0	1.10	0.0
27	12.7	63.49	29.6	8.7	Yes	128.76	61.70	92.26	B	11.5	1.81	5.0
28	16.9	69.82	36.3	7.2	Yes	130.68	74.01	111.30	B	8.0	1.15	8.5
29	11.4	56.66	32.4	5.9	Yes	95.58	65.87	99.25	B	6.5	1.15	5.0
30	11.2	52.60	36.7	6.9	Yes	126.62	74.69	112.37	B	4.5	0.86	6.0
31	18.2	68.01	32.8	8.3	Yes	136.12	67.67	101.44	B	3.0	0.44	5.0
32	17.3	58.25	33.9	10.2	Yes	172.89	70.80	105.66	B	7.0	1.20	–
33	13.5	54.56	31.2	7.3	Yes	113.88	64.09	96.26	B	6.5	1.19	8.0
34	15.2	57.46	35.8	8.1	Yes	144.99	73.41	110.19	B	7.0	1.22	6.0
35	6.7	49.93	29.0	5.0	Yes	72.50	58.86	88.84	B	2.5	0.50	5.5
36	14.8	64.98	26.1	8.9	Yes	116.15	55.15	82.20	B	9.5	1.46	0.0
37	17.6	56.64	36.1	9.6	Yes	173.28	74.71	111.78	B	7.0	1.24	0.0
38	11.6	59.38	27.2	6.3	Yes	85.68	55.84	84.01	B	0.0	0.00	3.0
39	8.4	59.15	26.7	5.7	Yes	76.10	54.60	82.28	B	10.0	1.69	4.0
40	11.6	63.19	29.7	6.5	Yes	96.53	60.81	91.48	B	7.5	1.19	8.0
41	13.5	50.89	36.3	8.7	Yes	157.91	74.66	111.93	B	9.5	1.87	0.0
42	17.0	62.27	33.6	9.6	Yes	161.28	69.89	104.45	B	8.5	1.37	6.5
43	15.4	57.68	34.6	9.5	Yes	164.35	71.76	107.33	B	6.5	1.13	0.0
44	21.0	69.14	35.3	8.4	Yes	148.26	72.57	108.84	C	0.0	0.00	2.0
45	17.2	66.88	32.7	7.5	Yes	122.63	67.10	100.77	C	6.0	0.90	0.0
46	18.3	57.92	33.7	9.5	Yes	160.08	70.03	104.69	C	9.0	1.55	0.0
47	19.2	74.85	35.6	8.0	No	142.40	72.98	109.55	C	7.0	0.94	0.0
48	17.0	64.33	33.2	8.3	Yes	137.78	68.44	102.61	C	6.0	0.93	7.0
49	19.0	63.04	35.6	7.8	Yes	138.84	72.89	109.47	C	6.0	0.95	0.0
50	24.5	75.62	34.9	9.9	Yes	172.76	72.55	108.42	C	8.5	1.12	2.0
51	21.4	64.40	35.3	11.2	No	197.68	74.07	110.32	C	3.0	0.47	0.0

because we felt that this was the best sample to test the functionality of smaller Levallois points (representative of small, mildly retouched triangular flakes) as arrowheads.

Each point was mounted using commercial adhesive on a 10 cm foreshaft made from 1/2″ (A: $n = 17$), 5/8″ (B: $n = 26$) or 3/4″ (C: $n = 8$) wooden dowels. A 2 cm notch was cut to fit the points and approximately a 3 cm hole was drilled into the opposite end. For the two points with the shortest length, this notch was cut down to 1.5 cm. The opposite side to the notch was shaved down to present a smooth plane from the distal end of the foreshaft to the base of the notch. The points were mounted in such a way as to minimize the difference in central planes between the foreshaft and the point. This usually resulted in the dorsal side of the point facing the notch, but a significant minority ($n = 9$) of the points were mounted in the opposite manner (Fig. 3A). This hafting method was chosen because it was quick, effective, and yielded consistent hafts (i.e., all points were equally well fastened to the same size foreshaft). We feel that using traditional or ethnographic hafting techniques would add additional compounding variables to the experiment.

These foreshafts were then fitted over the ends of commercial fiberglass arrows (6.4 mm diameter and 65.7 cm length). A length of tape was wrapped around the base of each foreshaft to help prevent splitting upon impact (Fig. 3B). The bow used had an approximately 40-lb pull; and an observer verified that it was drawn to its maximum each time (Fig. 3C).

2.1. Trial 1

The arrows were shot into a leather covered archery target from a distance of 4 m. The leather had an average thickness of 1.7 mm

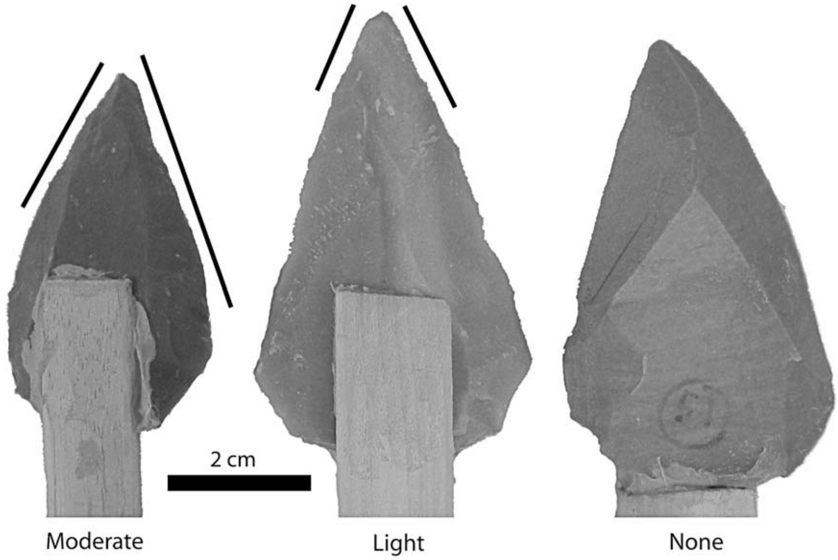

Fig. 1. Representative points. Any retouch on the points was isolated at the distal end, non-invasive, and either moderate or mild in extent.

and the target had an approximate density of 123 kg/m^3. Each penetration was measured from the distal end of the point to the top of the leather (to the closest 5 mm) and any wear or impact fractures were recorded.

2.2. Trial 2

The same points (excepting one that broke on a misfire) were then fired into a simulated animal carcass, again from a distance of 4 m. The simulated carcass consisted of an untreated goat skin, recovered from an earlier butchery experiment, stretched over a commercially purchased rack of ribs. Each shot was aimed for an area where no previous shots had broken the skin. Attempts were made to recover all fragments of broken points and penetration depth was recorded for each trial.

$$\text{Area} = 1/2\ \text{Width}*\text{Thickness}, \text{Perimeter} = 4\sqrt{s}, \quad \text{where } s = (1/2\ \text{Width})^2 + (1/2\ \text{Thickness})^2 (\text{after Hughes, } 1998: 354).$$

3. Results

3.1. Trial 1

The majority of the points ($n = 42$) penetrated through the leather and at least 5 cm into the archery target. Of these, six penetrated to a depth greater than 10 cm. A more relative scale of penetration depth is given as the ratio of penetration depth to tip length (henceforth referred to as penetration ratio). Measured in this way thirty-eight points penetrated past their maximum length (measured as the technical length of each point). Very few of the sample arrows ($n = 4$) failed to penetrate the target outright. Of these, one shattered on a misfire (by striking the wooden sawhorse supporting the target), and another evidenced some degree of breakage from a similar, though less dramatic, misfire. The two remaining points that failed to penetrate bounced off the target over five times each. Even these two evidenced some degree of marking from the leather, showing that there was some degree of penetration before the bounce. On one trial, the glue holding the point to the foreshaft failed. The point, however, remained lodged in the target. Five points that eventually penetrated were fired multiple times. This was usually because the target area was missed on the initial trail, though two points were launched a second time after bouncing off the target. All of the data recorded on point morphology and experimental performance are presented in Table 1.

Only three of the sample points evidenced any degree of macroscopic wear. Among these three, one was damaged after bouncing off the target. Another failed to penetrate entirely and evidenced some degree of crushing damage on its tip. The third was damaged on its first shot (which penetrated) and showed a small impact fracture on the distal end.

Following previous work on the relationship of point and foreshaft size to penetration (Hughes, 1998) measures of the maximum cross-sectional area and perimeter of the points were calculated. Hughes (1998) gives the formulae for tip cross-sectional area and perimeter as:

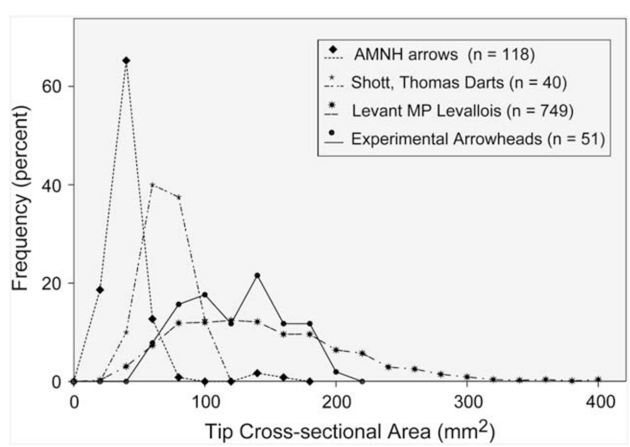

Fig. 2. Tip cross-sectional area of experimental points compared with other samples.

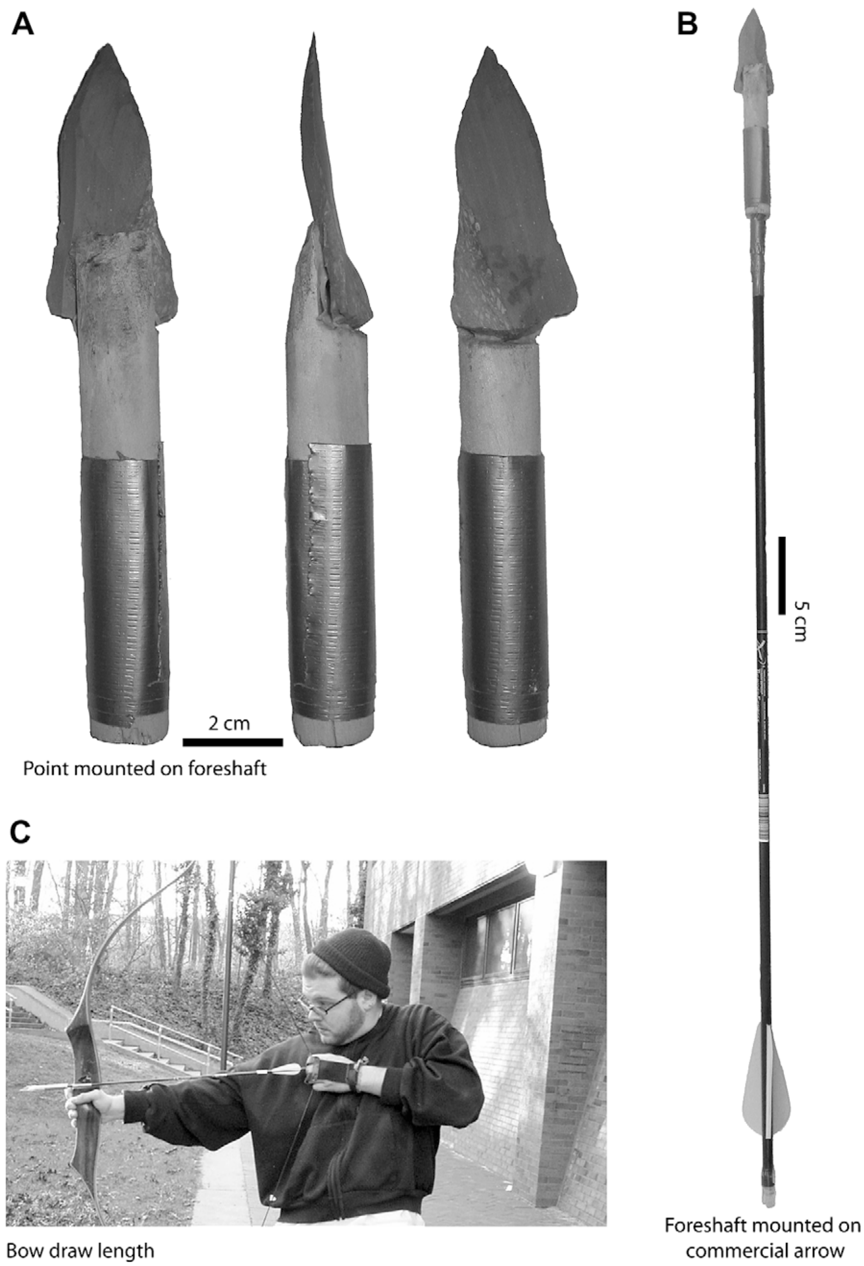

Fig. 3. Experimental protocols. A: point mounted on foreshaft, B: point and foreshaft mounted on commercial arrow, C. archer (MS) with bow at experimental draw length.

These formulae are provided for the analysis of North American dart and arrow tips, which are typically bifacially worked and thus have a cross-section best approximated by a rhombus. Given the more triangular cross-section of these simple points it seems judicious to modify the perimeter formula to represent this. Thus, an alternate formula is presented as:

$$\text{Perimeter} = \text{Width} + 2^{*}\sqrt{\left((1/2\ \text{Width})^2 + \text{Thickness}^2\right)}$$

See Fig. 4 for a geometric demonstration of these two models. Both the altered form of the method presented in Hughes (1998) and this new method were used to calculate the cross-sectional area of each point (see Table 1).

Once the penetration ratio was calculated, a series of statistical tests was performed to track which variables (thickness, width, perimeter, and area) were correlated with penetration. Due to the difference in measurement scales between the penetration (nearest half-centimeter) and the rest of the variables (nearest millimeter), a Spearman's *rho* nonparametric correlation was used. Please refer to Table 2 for these correlations. A Mann–Whitney U test ($U = 92$, $p = 0.044$) also indicates that those points without retouch had significantly higher penetration ratios than those with retouch. Fig. 5 shows graphically the relationship between the penetration ratio and cross-sectional perimeter. Using the penetration ratio, which includes the technical length of each point, introduces some error as the technical length is correlated with width and thickness. When simple penetration depth is correlated with the width, thickness, the same relationships among variables are apparent, though not as strongly represented (Table 2). However, we feel that the penetration ratio, scaling for length, gives a more accurate metric of the true effectiveness of each point.

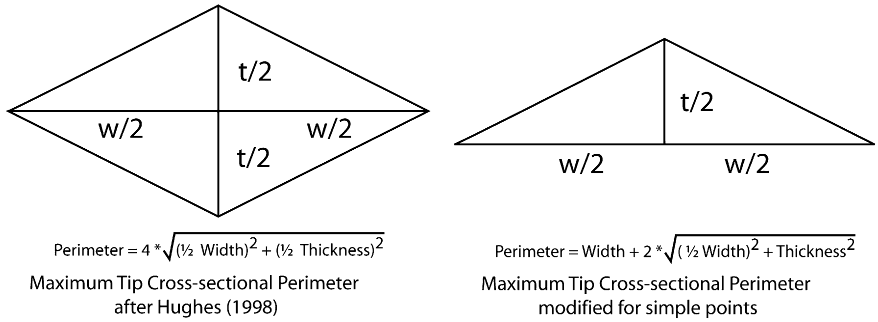

Fig. 4. The two estimates of tip cross-sectional perimeter.

3.2. *Trial 2*

The second trial demonstrated that when these points impact a target with higher and more variable density (mainly bone) they tend to either fracture on impact or fail to penetrate. Only the smallest and thinnest of the points (those on the extreme range of archaeological points) penetrated the animal target sufficiently. Of the fifty points remaining for this trial, only thirteen penetrated the target to a depth greater than their length. All of these points were among smallest 50% of the points by cross-sectional area, and eight of them were within the lowest 25%. Nearly all breakages occurred during the first time they were shot. Fractures seen tended to be “tongued,” step, and burin fractures (Fig. 6). A few points fractured in multiple places, resulting in small trapezoidal pieces similar to the fragment found in the equid vertebra at Umm el Tlel (Boëda et al., 1999). Given the high number of breakages in this trial, only rough measures of penetration depth were taken (Table 1).

4. Discussion

The most important implication of this experiment lies in the significant correlation between tip perimeter and penetration ratio. Intuitively and mathematically, increasing point width while keeping the thickness constant should have a strong effect on the perimeter (as the object approaches two dimensions). Conversely, increasing the thickness has a stronger effect on the area (as the thickness approaches the width). Even within the small sample in this study, we see clearly that point width and perimeter are more strongly correlated with the penetration ratio than are either cross-sectional area or thickness (Table 2). This indicates that the relationship between tip cross-sectional area and tip-usage seen by other authors may be tracking the perimeter (because area and perimeter are derived from the same measurement and highly correlated). Thus tip cross-sectional perimeter may actually be a better indicator of potential use than tip cross-sectional area. Further experiments, and analysis of metal point collections (which have fewer shape constraints than stone), are currently underway to address some of these questions.

Finally, the result of a higher penetration ratio for unretouched points is at first puzzling given that Odell and Cowan (1986) found that retouched points were slightly more effective. This may be explained by the increased drag on a point with steep retouch scars along its leading surface. It is possible that points with a small amount of retouch concentrated at its tip actually function less well as projectile armatures, but those with retouch sufficient to impose a more effective form (see Hughes, 1998 for a discussion of this optimum form) begin to overcome the effects of drag.

The first trial seemed to indicate that smaller sized Levallois points could have been used as effective projectile points (i.e., penetrate, on average, relatively deeply into a uniform target). However, the second trial demonstrated that such usage results in high incidences of breakage. Many of the points were able to puncture the skin, and in a few cases even penetrate through the ribs, but this was not the central tendency in the experimental data. While the occasional breakage of points into trapezoidal and pentagonal-shaped fragments, like the one from Umm el Tlel, may be representative of high-velocity impacts, we found no consistent trend for such breakages. The Levallois points used in this trial, even the smallest ones, tended to fracture on bone, or simply bounce off the target. Despite this, we are unable to rule out isolated uses of individual Levallois points, particularly those with very small cross-sectional areas/perimeters as projectile points. However, if smaller Levallois points were being used as projectile armatures, it appears that an overall functional shape could have been more highly valued than durability. As a caveat, these findings are germane only to small Levallois points and cannot be extrapolated to Levallois points as a typological class. The picture for all Levallois points as a whole is likely quite a bit more complicated both because the class contains great variation in size and overall shape, and because other experimental use of larger Levallois points as thrusting spear amateurs demonstrates that most points are both effective and highly durable (Shea et al., 2001, 2002).

Taking all these considerations into account, these experiments suggest that the Umm el Tlel point, with a cross-sectional perimeter at the high end of our experimental sample (roughly estimated at 97.7 mm (Boëda et al., 1999: 398)) was not a projectile point. Rather, it was most likely the stone tip of a hand-cast spear or thrusting spear, one used more or less in the same way as inferred for other Levallois points from Levantine contexts and (Shea, 1988) and in the same way as most stone-tipped ethnographic spears, to dispatch a large mammal already disabled or immobilized by some other method (Churchill, 1993). The hypothesis that there are former projectile points lurking unrecognized among Levallois points from Levantine Middle Paleolithic contexts is not supported by these data.

Table 2
Correlation coefficients and significance levels for penetration ratio and penetration depth.

	Width		Thickness		Area		Perimeter	
Penetration ratio	−0.484	$p < 0.001$	−0.282	$p < 0.1$	−0.422	$p < 0.01$	−0.484	$p < 0.001$
Penetration depth	−0.248	$p < 0.1$	0.042	$p > 0.5$	−0.080	$p > 0.5$	−0.242	$p < 0.1$

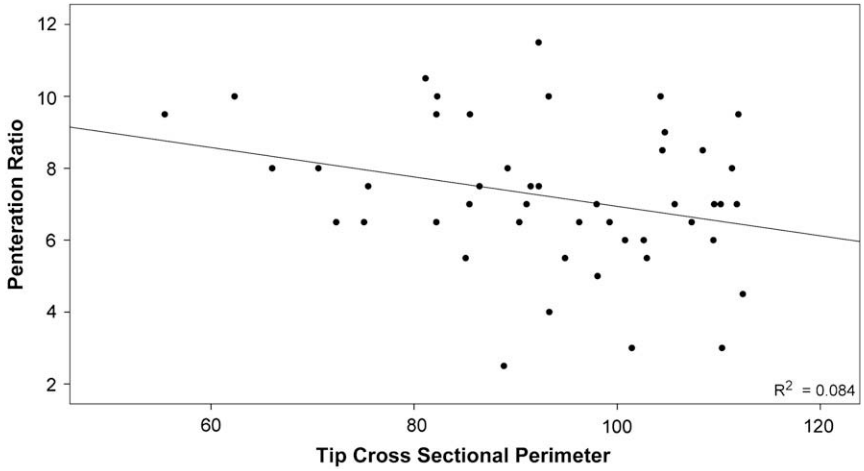

Fig. 5. Scatter plot with regression showing the relationship between tip cross-sectional perimeter and penetration ratio.

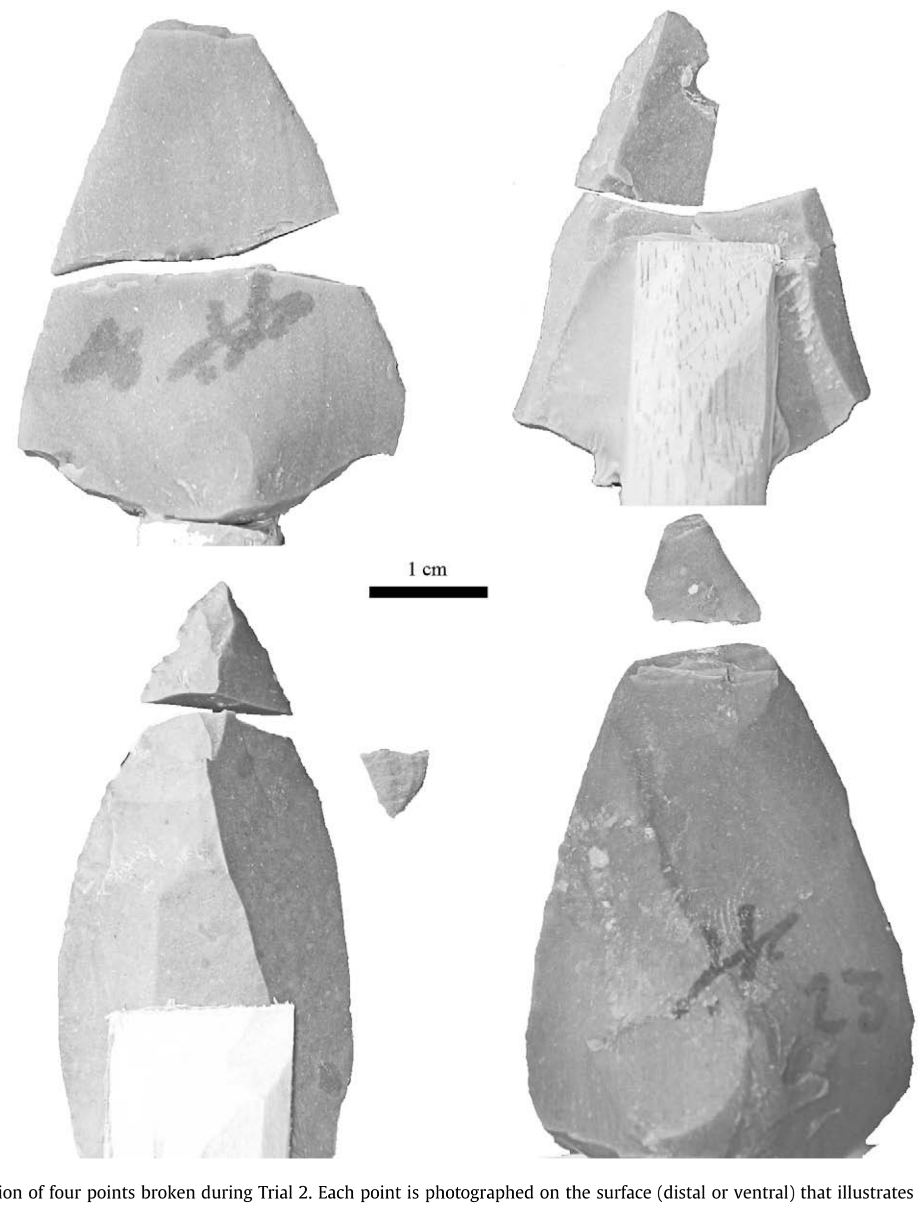

Fig. 6. Selection of four points broken during Trial 2. Each point is photographed on the surface (distal or ventral) that illustrates the break best.

5. Conclusions

This preliminary study yielded two main results. First, it statistically shows, that for a limited sample, penetration is more strongly correlated with point width and cross-sectional perimeter than with thickness or cross-sectional area. This seems to show that while cross-sectional area functions well as a classification system for lithic points, the underlying geometric relationships indicate that the closely related cross-sectional perimeter may have more explanatory power. Second, the slightly better penetration of unretouched points indicates that there may be a threshold before which retouch actually decreases the utility of stone points. It is promising that such strong correlations are found even in a limited sample size. Further experimental work and analysis of archaeological and ethnographic collections needs to be undertaken to fully understand both the utility of the methods used to quantify penetration of stone projectile tips, and of the possible use of relatively "simple" projectile point forms.

Experimental archaeology demonstrates the possible, not the probable (Thomas, 1986). Nothing in these experiments proves that any Levallois point, triangular flake, or similar stone artifact made before 40–50 Kya (or afterwards for that matter) was ever used as an arrowhead. On the other hand, morphometric assessments of stone point function can test hypotheses about stone tool function in explicitly quantitative, parametric and probabilistic/statistical terms that remain elusive goals for the principal alternative approaches to reconstructing projectile point function, microwear and residue analysis. Over the course of an hour, a single archaeologist using a simple set of calipers can measure the variables necessary to calculate tip cross-sectional area and perimeter for dozens of individual artifacts. Using a computer spreadsheet, these dozens of calculations can be performed in a fraction of a second. To thoroughly check for microwear or residues on an equivalent number of artifacts would take days, even if one only counted the time spent actually looking at tools under the microscope or analyzing residues. The resulting wear and residue interpretations provide a level of detail and specificity far greater than one can achieve by large-scale comparisons of tool morphometry, but these interpretations remain hypotheses that are difficult to falsify in an objective way. In contrast and in principle, the hypothesis that a particular prehistoric stone point was a projectile point can be refuted by showing that the values of its key ballistic dimensions are outside the range of effective experimental projectiles.

Obviously, the key to such hypothesis-testing lies in amassing a large body of observations about the performance of various stone points under a variety of tightly-controlled experimental conditions. (Comparing archaeological points to ethnohistoric ones of known function was a first step in this research agenda (Shea, 2006), but it was always intended as a first step only.) The value of ballistically-significant variables will differ among points of contrasting overall geometries, such that measurements for effective triangular points will necessarily differ from those of foliate bifaces, tanged points, or backed pieces. Hundreds, or even thousands, of experiments will have to be conducted before we can work out the algorithms necessary for predictive models of stone projectile point performance. This kind of research program clearly calls for the use of mechanical aids, such as the calibrated crossbows that have been used by some experimenters. In the experiment outlined above, we focused on penetration, and to a lesser degree durability, as a proxy for projectile effectiveness. It is clear that this is a more complicated issue; with range and accuracy playing a significant role on projectiles fired over a longer distance than the few meters in our experiment. A further crucial technical improvement is the need for standardization of experimental targets. For this, we believe that a simulated material like the ballistic jell that is used in forensic studies would be appropriate (Jussila, 2004), although potentially it would need to be augmented by the inclusion of simulated skin and bones. In this, archaeologists will have to consult with colleagues in the forensic sciences.

We mention these future directions in archaeological research on the origins of projectile technology for several reasons. First, this is clearly work that needs to be undertaken by more than one research group, and we wish to encourage other experimenters. Secondly, it is important that these experiments be performed under controlled conditions with careful measurement of experimental variables. Shooting a few stone-tipped arrows into an animal carcass and declaring the experiment a "success" does not advance this experimental program as much as do experiments in which weapon morphology, loading conditions, and the physical characteristics of the target were tightly-controlled. Lastly, we want to caution the readers of this paper about the preliminary nature of our observations about the functional qualities of small triangular flakes. We think these experiments show that point perimeter works better as a predictor of point penetration than tip cross-sectional area, but archaeologists' understanding of projectile point performance is still in a very rudimentary state. Nobody should take away from this paper the notion that they can, by simple measurements alone, show a particular Levallois point or an artifact belonging to some allied tool type was a projectile point without recourse to other lines of evidence, including microwear, residue analysis, zooarchaeology, and other contextual clues from the archaeological record.

Projectile technology is niche-broadening technology. Projectile weapons decrease the risks associated with preying on large, dangerous prey species and they increase the returns on hunting smaller, fast-moving terrestrial species, birds, and fish. All known historical and ethnographic human societies use projectile technology (or they are descended from ones who did), and few known humans societies have long abandoned its use. The use of projectile weaponry appears to have had a transformative effect on the evolution of *H. sapiens*. No other organism has a niche as wide, stable, and variable, as does *H. sapiens* and much of that niche's width, stability, and variability, reflects the use of projectile technology. In reconstructing the course of our species' evolutionary history, it is clearly important to know whether projectile technology was (1) in use among *H. sapiens*' precursors in Africa, (2) used by some ancient *H. sapiens* populations and not others, and (3) developed by other now extinct hominin species, such as the Neandertals and *Homo floresiensis*. Answering these research questions requires that we set in place robust methods for testing hypotheses about hypothetical prehistoric projectile weapons. The experiments documented in this paper are a small contribution to this emerging research agenda.

Acknowledgements

The authors would like to thank Danielle Royer, Ian Wallace, and Amanuel Beyin for helpful comments and criticism. We would also like to thank Zach Davis, and Kyle Brown for providing the replicated points used in this study and Dody Ben-Amy for creating the replications. An earlier draft of this work benefited greatly from comments by Michael Shott and two anonymous reviewers. Initial funding for the experimental collection was provided by a Wenner-Grenn Foundation for Anthropological Research grant to JJS.

References

Bar-Yosef, O., 2002. The upper paleolithic revolution. Annual Review of Anthropology 31, 363–393.

Binford, L.R., 1989. Isolating the transition to cultural adaptations: an organizational approach. In: Trinkaus, E. (Ed.), The Emergence of Modern Humans: Biocultural Adaptations in the Later Pleistocene. Cambridge University Press, New York, pp. 18–41.

Boëda, E., Geneste, J.-M., Griggo, C., Mercier, N., Muhesen, S., Reyss, J.L., Taha, A., Valladas, H., 1999. A Levallois point embedded in the vertebra of a wild ass (*Equus africanus*): hafting, projectiles and mousterian hunting weapons. Antiquity 73, 394–402.

Bordes, F., 1961. Typologie du paléolithique ancien et moyen. Delmas, Bordeaux.

Brooks, A.S., Yellen, J.E., Nevell, L., Hartman, G., 2006. Projectile technologies of the African MSA: implications for modern human origins. In: Hovers, E., Kuhn, S.L. (Eds.), Transitions before the Transition. Plenum/Kluwer, New York, pp. 233–256.

Chase, P.G., 1989. How different was middle paleolithic subsistence? A zooarchaeological perspective on the middle to upper palaeolithic transition. In: Mellars, P.A., Stringer, C.B. (Eds.), The Human Revolution: Behavioural and Biological Perspectives on the Origins of Modern Humans. Edinburgh University Press, Edinburgh, pp. 321–337.

Cheshier, J., Kelly, R.L., 2006. Projectile point shape and durability: the effect of thickness:length. American Antiquity 71, 353–364.

Churchill, S.E., 1993. Weapon technology, prey size selections, and hunting methods in modern hunter-gatheres: implications for hunting in the palaeolithic and mesolithic. In: Peterkin, G.L., Bricker, H., Mellars, P.A. (Eds.), Hunting and Animal Exploitation in the Later Palaeolithic and Mesolithic of Eurasia. American Anthropological Association, Washington, DC, pp. 11–24. Paper No. 4.

Dennell, R.W., 1983. European Economic Prehistory. Academic Press, New York.

Flenniken, J.J., Raymond, A.W., 1986. Morphological projectile point typology: replication, experimentation and technological analysis. American Antiquity 51, 603–614.

Gao, X., Norton, C.J., 2002. Critique of the Chinese "middle paleolithic". Antiquity 76, 397–412.

Habgood, P.J., Franklin, N.R., 2008. The revolution that didn't arrive: a review of Pleistocene Sahul. Journal of Human Evolution 55, 187–222.

Henshilwood, C.S., Marean, C.W., 2003. The origin of modern human behavior: critique of the models and their test implications. Current Anthropology 44, 627–651.

Hughes, S.S., 1998. Getting to the point: evolutionary change in prehistoric weaponry. Journal of Archaeological Method and Theory 5, 345–408.

Jussila, J., 2004. Preparing ballistic gelatine – review and proposal for a standard method. Forensic Science International 141, 91–98.

Kaufman, D., 2002. Re-evaluating subsistence skills of Levantine middle and upper Paleolithic hunters: a comparison of the faunal assemblages. Oxford Journal of Archaeology 21, 217–230.

Klein, R.G., 2008. Out of Africa and the evolution of human behavior. Evolutionary Anthropology 17, 267–281.

Knecht, H., 1997. The history and development of projectile technology research. In: Knecht, H. (Ed.), Projectile Technology. Plenum, New York, pp. 3–36.

Kuhn, S.L., Stiner, M.C., 2001. The antiquity of hunter-gatherers. In: Panter-Brick, C., Layton, R.H., Rowley-Conwy, P. (Eds.), Hunter-gatherers: An Interdisciplinary Perspective. Cambridge University Press, Cambridge, pp. 99–142.

Kuhn, S.L., Stiner, M.C., 2006. What's a mother to do? Division of labor among Neandertals and modern humans in Eurasia. Current Anthropology 47, 953–980.

Lombard, M., 2005. A method for identifying stone age hunting tools. South African Archaeological Bulletin 60.

Lombard, M., Pargeter, J., 2008. Hunting with Howiesons Poort segments: pilot experimental study and the functional interpretation of archaeological tools. Journal of Archaeological Science 35, 2523–2531.

McBrearty, S., 2007. Down with the revolution. In: Mellars, P.A., Boyle, K., Bar-Yosef, O., Stringer, C.B. (Eds.), Rethinking the Human Revolution. McDonald Institute for Archaeological Research Monographs, Cambridge, pp. 133–152.

McBrearty, S., Brooks, A.S., 2000. The revolution that wasn't: a new interpretation of the origin of modern human behavior. Journal of Human Evolution 39, 453–563.

Mellars, P.A., 1973. The character of the middle–upper paleolithic transition in southwest France. In: Renfrew, C. (Ed.), The Explanation of Culture Change. Duckworth, London, pp. 255–276.

Mellars, P.A., 2007. Rethinking the human revolution: Eurasian and African perspectives. In: Mellars, P.A., Boyle, K., Bar-Yosef, O., Stringer, C.B. (Eds.), Rethinking the Human Revolution. McDonald Institute for Archaeological Research Monographs, Cambridge, pp. 1–14.

Mellars, P.A., Stringer, C.B., 1989. The Human Revolution: Behavioural and Biological Perspectives on the Origins of Modern Humans. Edinburgh University Press, Edinburgh.

O'Connell, J., Allen, J., 2007. Pre-LGM Sahul (Pleistocene Australia-New Guinea) and the archaeology of early modern humans. In: Mellars, P.A., Boyle, K., Bar-Yosef, O., Stringer, C.B. (Eds.), Rethinking the Human Revolution. McDonald Institute for Archaeological Research Monographs, Cambridge, pp. 395–410.

Odell, G.H., Cowan, F., 1986. Experiments with spears and arrows on animal targets. Journal of Field Archaeology 13, 194–212.

Plisson, H., Beyries, S., 1998. Pointes ou outils triangulaires? Données fonctionnelles dans le moustérien levantin. Paléorient 24, 5–24.

Shea, J.J., 1988. Spear points from the middle paleolithic of the levant. Journal of Field Archaeology 15, 441–450.

Shea, J.J., 1997. Middle paleolithic spear point technology. In: Knecht, H. (Ed.), Projectile Technology. Plenum, New York, pp. 79–106.

Shea, J.J., 2006. The origins of lithic projectile point technology: evidence from Africa, the Levant, and Europe. Journal of Archaeological Science 33, 823–846.

Shea, J.J., 2007. Behavioral differences between middle and upper paleolithic *Homo sapiens* in the east Mediterranean Levant: the roles of intraspecific competition and dispersal from Africa. Journal of Anthropological Research 64, 449–488.

Shea, J.J., 2009. The impact of projectile weaponry on late Pleistocene human evolution. In: Hublin, J.-J., Richards, M. (Eds.), The Evolution of Hominid Diets: Integrating Approaches to the Study of Paleolithic Subsistence, Springer, New York, pp. 187–197.

Shea, J.J., Brown, K., Davis, Z., 2002. Controlled experiments with middle paleolithic spear points: Levallois points. In: Mathieu, J.R. (Ed.), Experimental Archaeology: Replicating Past Objects, Behaviors, and Processes. British Archaeological Reports, International Series 1035. Oxford, UK, pp. 55–72.

Shea, J.J., Davis, Z., Brown, K., 2001. Experimental tests of middle paleolithic spear points using a calibrated crossbow. Journal of Archaeological Science 28, 807–816.

Shott, M.J., 1997. Stones and shafts redux: the metric discrimination of chipped-stone dart and arrow points. American Antiquity 62, 86–101.

Stern, N., 2009. The archaeological signature of behavioral modernity: a perspective from the southern periphery of the modern human range. In: Lieberman, D.E., Shea, J.J. (Eds.), Transitions in Prehistory: Essays in Honor of Ofer Bar-Yosef, Oxbow, Oxford, pp. 255–287.

Stiner, M.C., 1993. Modern human origins – faunal perspectives. Annual Review of Anthropology 22, 55–82.

Stiner, M.C., Kuhn, S.L., 2006. Changes in the "connectedness" and resilience of paleolithic societies in Mediterranean ecosystems. Human Ecology 34, 693–712.

Stiner, M.C., Munro, N., Surovell, T., Tchernov, E., Bar-Yosef, O., 1999. Paleolithic population growth pulses evidenced by small animal exploitation. Science 283, 190–194.

Thomas, D.H., 1978. Arrowheads and Atl-atl Darts – how stones got shaft. American Antiquity 43, 461–472.

Thomas, D.H., 1986. Points on points: a reply to Flenniken and Raymond. American Antiquity 51, 619–627.

Waweru, V., 2007. Middle stone age Archaeology of the Cartwright's site, Kenya, PhD thesis, Department of Anthropology, University of Connecticut.

White, R.H., 1982. Re-thinking the middle/upper paleolithic transition. Current Anthropology 23, 169–176.