ANTHROPOLOGY

Bow-and-arrow, technology of the first modern humans in Europe 54,000 years ago at Mandrin, France

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Consensus in archaeology has posited that mechanically propelled weapons, such as bow-and-arrow or spear-thrower-and-dart combinations, appeared abruptly in the Eurasian record with the arrival of anatomically and behaviorally modern humans and the Upper Paleolithic (UP) after 45,000 to 42,000 years (ka) ago, while evidence for weapon use during the preceding Middle Paleolithic (MP) in Eurasia remains sparse. The ballistic features of MP points suggest that they were used on hand-cast spears, whereas UP lithic weapons are focused on microlithic technologies commonly interpreted as mechanically propelled projectiles, a crucial innovation distinguishing UP societies from preceding ones. Here, we present the earliest evidence for mechanically propelled projectile technology in Eurasia from Layer E of Grotte Mandrin 54 ka ago in Mediterranean France, demonstrated via use-wear and impact damage analyses. These technologies, associated with the oldest modern human remains currently known from Europe, represent the technical background of these populations during their first incursion into the continent.

INTRODUCTION

Consensus in the archaeology of human origins has posited that mechanically propelled weapons, such as bow-and-arrow or spear-thrower-and-dart combinations, appeared abruptly in the Eurasian archaeological record with the arrival of anatomically and behaviorally modern humans and the Upper Paleolithic (UP) after 45 to 42 thousand years (ka) ago (note S1) (*1*–*3*). Here, we present the earliest evidence for bow-and-arrow technology in Eurasia from Layer E of Grotte Mandrin in Mediterranean France. These projectile technologies represent the technical background of expanding modern humans during their first incursion into Europe ~54 ka ago (*4*). The production of lithic artifacts in Mandrin's Layer E was focused on standardized tiny points, some clustering around only 1 cm in length (Figs. 1 and 2), thus far unseen in archaeological assemblages of this age and representing a main structural difference between Neanderthal and modern human social and material organization. These technologies may have given modern humans a competitive advantage over local Neanderthal societies.

Grotte Mandrin is a vaulted rock shelter directly overlooking the middle valley of the Rhône River. Mandrin records a reference archaeological succession, for it contains all of the phases currently known for the last Neanderthal societies, right up to the emergence of the UP (*5*–*7*). Each archaeological layer has yielded a rich lithic industry and paleontological remains (*4*). Layer E yielded 2267 lithic elements attributed to the Neronian, a "culture" entirely oriented toward the production of standardized Levallois points, technologically obtained after laminar phases (*5*–*7*). Quantitatively, blades, bladelets, and a variety of points represent 75.1% of all blanks. The production of these points was technically highly controlled and focused on two categories: larger points from 30 to 60 mm in maximum length and microlithic points below 30-mm maximum length and sometimes as small as 10 mm, termed here "nanopoints." The distinction between these two categories is technological, not based on size. The larger points were produced on the basis of laminar technology, initiated by a crested blade extraction and followed by unipolar blade production that configured the core geometry to extract technologically well-defined points. The micro/nanopoints were not produced simply as a smaller version of that process on very reduced cores but rather via "core-on-flake" knapping of blanks produced while making the larger points (Figs. 1 and 2, fig. S1, and note S2) (*5*).

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RESULTS

A precise macroscopic and microscopic use-wear analysis (see Materials and Methods) was undertaken on 852 artifacts—highly controlled points and micro/nanopoints (n = 476), regular bladelets (n = 230), and blades and flakes (n = 146)—to find any wear or micropolish. We conducted an experimental program called Initiarc, based on Mandrin E point replicas, including both nonpercussion (pressure and taphonomic, n = 219) (*8*) and percussion (throwing/thrusting, n = 82) actions to evaluate the potentialities of these specific stone points and their impact damages when used as weapons (Fig. 3, fig. S3, and note S3). To detect whether a tool was used kinetically, we consider not only the presence, type, or patterns of diagnostic impact fractures (DIFs) but also the frequency, combination of diagnostic characters, and the location of these DIFs on the lithic piece (see Materials and Methods; Fig. 4, and note S3).

The first results of the use-wear analysis show that 10.4% of the archaeological elements, all technological categories included, are devoid of any macro- or microscopic trace of use (n = 89; within the Initiarc experimental program, 8.3% of the points show no

Fig. 1. Mandrin E lithic artifacts. (1 to 13) Distal of nanopoints, micropoints, and points. (14 to 17) Distal of Soyons points. (18 to 22) Mesial of bladelets, micropoints, and points. (23 to 35) Proximal of nanopoints, micropoints, and points. (36 to 47) Sub-full and full nanopoints, micropoints, and points.

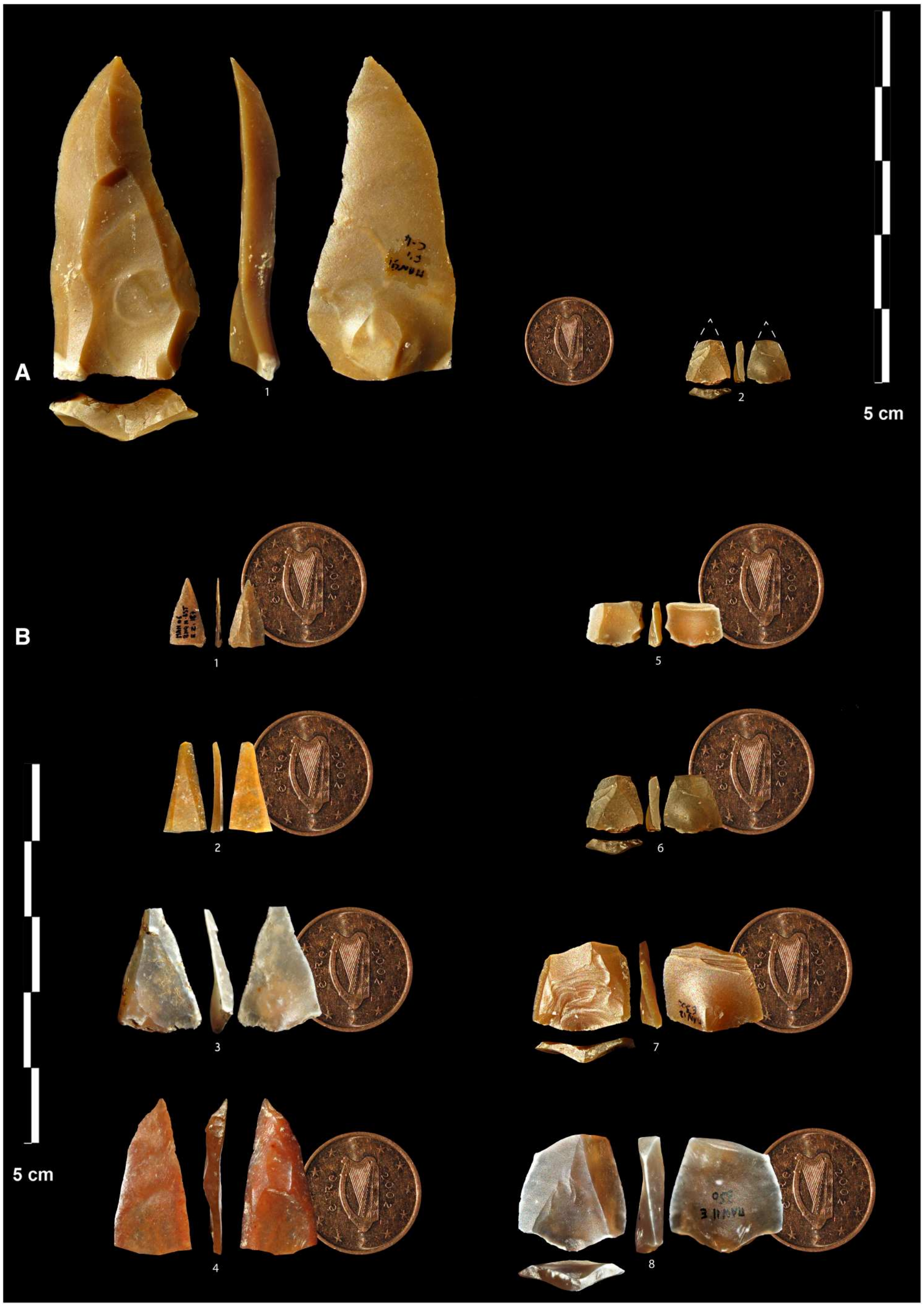

Fig. 2. Mandrin E. Lithic points. (**A**) Large point (1) versus nanopoint (2). (**B**) Neronian micropoints and nanopoints; (1 to 3) elongated nanopoints, (4) pointed nanopoint, (5 and 6) nanopoints, and (7 and 8) micropoints. Graphic scale is 1 Euro cent (diameter, 16.25 mm).

trace; note S3). Macro- and/or microscopic traces that were clearly identifiable as resulting from taphonomic action were identified on 4.1% of the blanks (n = 35). Macro- and/or microscopic traces that were too ambiguous to deduce with certainty a function were observed on 15.4% of the pieces (n = 131). This gives a total of 255 pieces (29.9%) whose anthropic use is uncertain, if not absent, within the 852 pieces selected. The rest of the sample shows evidence of anthropic activity, representing 70.1% of the series studied (n = 597). Of the 597 pieces used, 82.4% were fractured (n = 492). For those for which the cause could be established (n = 269), fracturing occurred in both modes of operation, 20.5% in a nonpercussive manner and 34.1% in a percussive action. For the remaining 223 pieces, no interpretation could be stated. Physical traces of past use were observed on 383 elements: 172 pressure actions, 196 percussion actions, and 15 pieces presenting both. The proportions obtained within these different categories of

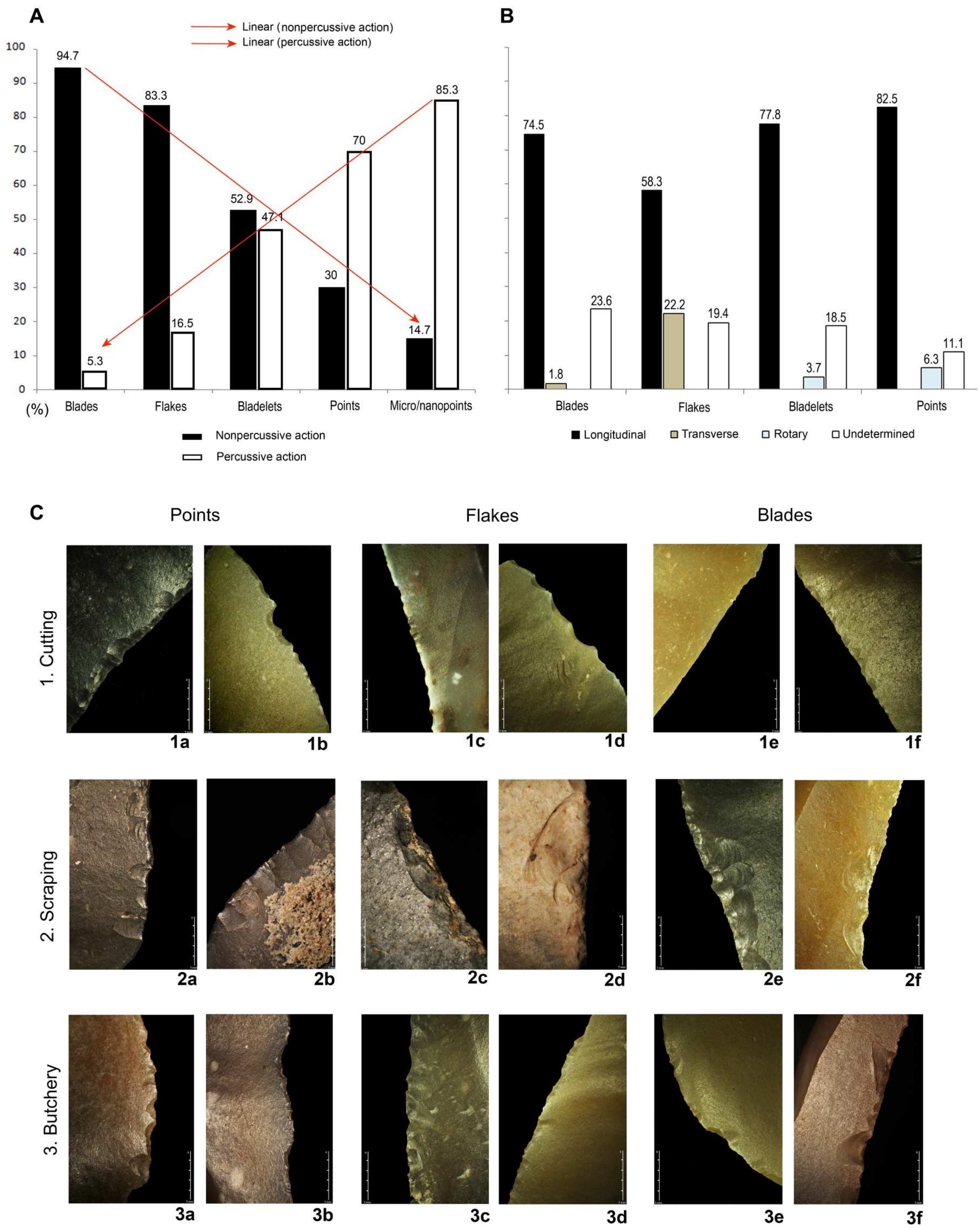

Fig. 3. Pressure motions on archaeological flakes, blades, and points from Mandrin Layer E. (**A**) Repartition of actions by technical categories. (**B**) Repartition of movements by technical categories. (**C**) (1) Cutting action, (2) scraping action, and (3) butchery activities.

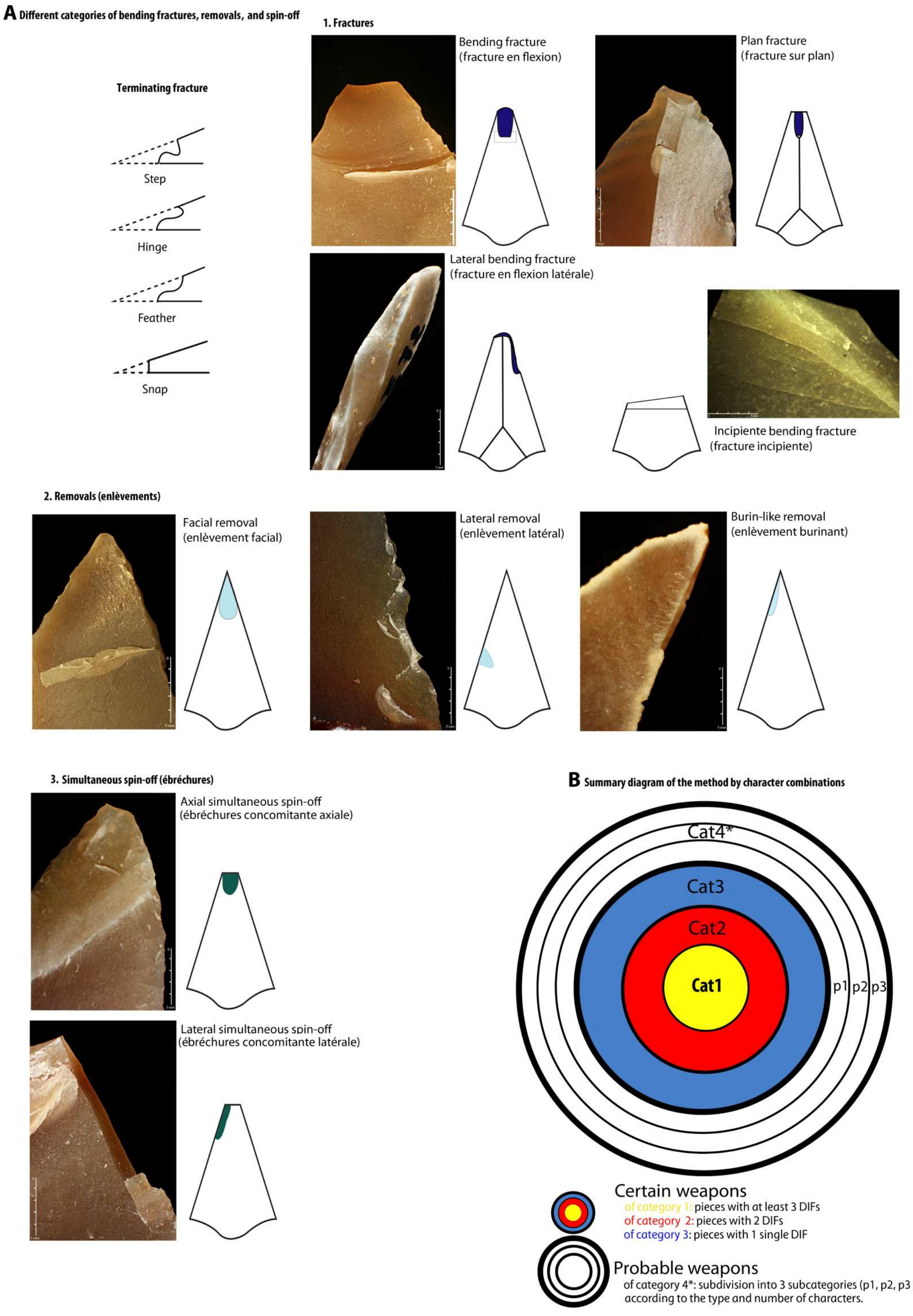

Fig. 4. Methodological elements for determining armaments. (**A**) Different categories of stigmata (bending fractures, removals, and simultaneous spin-off). (**B**) Summary diagram of the method by character combinations.

objects clearly show an obvious distinction in the modes of action with a predominance of pressure gestures on blades and flakes and a preponderance of percussive actions on points (points, micropoints, and nanopoints; Fig. 3A). Each technological category bears evidence of having been used in different tasks; blades and flakes were almost exclusively used in domestic activities (meat cutting, tanning skins, etc.), and points and micro/nanopoints were almost exclusively used in percussive actions, such as a part of propelled or thrusted weapons. The bladelets occupy a clearly intermediate position where nonpercussive actions slightly dominate with 52.9% compared to 47.1% percussive actions.

In pressure motions, points and micro/nanopoints were purposely grouped together within the same category. In isolation, the number of microlithic supports engaged in pressure activities was too small (micropoint, $n = 9$; nanopoint, $n = 1$) to be compared to the rest of the sample. Cutting actions amply predominate over the rest of the observed movements ($n = 128$; Fig. 3B). This type of movement is mainly representative of butchery activities, which include cutting meat, removing tendons, skinning, eviscerating, and disarticulating limbs. All technological categories bear stigmata specific to this type of movement, with a slight overrepresentation among the points (82.5%). Traces left during scraping actions are observed on less than 10 pieces (eight flakes and one blade) and are totally absent within the bladelets and micro/nanopoints (Fig. 3C). Rotary movements occupy an anecdotal place with only four objects having been used to drill, all having a pointed end (two points, one micropoint, and one bladelet). In 17.7% of cases, the movement could not be clearly identified, and although all the pieces show a purely nonpercussive action, their exact function remains undetermined.

Percussive actions concern 83.2% of the points but only, anecdotally, the flakes or blades (4.6%; Fig. 3A). Last, no flakes or blades show any characteristic traces that would allow us to consider their use as weapons. This means that in Layer E of Mandrin, the technical categories of blades and flakes, retouched or not, are mostly not directly related to hunting activities. The macrofracture study shows that the points (points, micropoints, and nanopoints) primarily had this function. The functional analysis also shows that not all the points were systematically destined to become armatures for weapons: 21.3% of large points were used in domestic activities, mainly in butchery work (skinning, evisceration, disarticulation, meat cutting, etc.; Fig. 3C).

A total of 131 DIFs were attested on 71 pieces (35 points, 25 micropoints, and 11 nanopoints); just over a third (33.8%) of points record between two and four DIFs per piece, with 12.7% having a minimum of three DIFs per piece [Figs. 5 to 7 and note S3 ("DIFs" in the "Archaeological results" section)]. These DIFs show strong similarities with those obtained during our experimental use of such points as projectiles and those reported from more than four decades of similar experimental work [Fig. 8 and note S3 (Projectile experimental results)] (*9*–*22*). When considered by the minimum number of individual, as many as 15.5% of all points present DIFs from violent axial impact on their distal end that are strictly diagnostic of their use as weapons [9.7% of the points, 30.2% of the micropoints, and up to 36.7% of the nanopoints; note S3 (Archaeological results) and table S1].

Mode of weapon use

The well-defined bilaterally symmetrical transverse section of the points and micropoints (Figs. 1 and 2) and the location of their DIFs (Figs. 5 to 7) indicate that weapons were all distally (rather than laterally) hafted. This location at the distal end of a shaft is important, as it is well attested through ethnographic records that when distally armed, the maximum width of the points directly constrains their shafts' maximum diameter (*9*, *11*, *16*, *20*, *22*–*31*). Experiments explain that situation and show that, when distally armed, a projectile of smaller diameter than its shaft is unable to efficiently penetrate its target. In Mandrin E, more than 75% of the micro- and nanopoints present a maximum width of 15 mm and reach 10 mm (the width was taken at the widest point of the piece), or below, for almost 40% of them, meaning that ~40% of these points were armed at the distal end of shaft of less than 10 mm in maximum diameter (Fig. 8 and fig. S1). This diameter of 10 mm represents an important boundary. Ethnographic stone weapons whose shafts' maximum diameter is below 10 mm are exclusively from bow technologies (*11*, *16*, *24*, *26*, *28*–*31*). This is linked with the intrinsic ballistic limits of the other categories of delivery systems that cannot deliver sufficient energy to efficiently propel such tiny weapons armed on narrow shafts. These limits are also well documented when reproduced experimentally, whereas, only when delivered by bow, these tiny weapons with narrow shafts are remarkably efficient. These experiments show that the low kinetic energy of such light weapons can, in that specific configuration, exclusively be corrected by the high-speed mechanical propulsion of a bow. These tiny points of less than 10-mm breadth and that are distally armed are ruled by morphological and ballistic constraints that strictly limit them to the use of bow-and-arrow technology at the exclusion of any other delivery system (notes S3 and S4).

Archaeological and ethnographic data show that DIF proportions are generally clustered around or below 10% (note S1). Higher representations are known for kill sites only, e.g., the Casper site (43%) or Stellmoor (42.2%), where the lithics recovered are primarily related to specialized hunting activities (*32*–*34*). The high DIF frequency of the Mandrin E tiny points (30.2% of the micropoints and 36.7% of the nanopoints) implies that at least those of <10-mm breadth were made for and used repeatedly as arrows. The Mandrin E points are technically highly standardized, providing morphological and dimensional homogeneity (Figs. 1, 2, and 8, fig. S1, and note S2). These morphometric traits are thus far unknown in the Eurasian Middle Paleolithic (MP) record but are commonly seen in mechanically propelled projectiles.

Tip cross-sectional area

The tip cross-sectional area (TCSA) values (*20*, *21*, *35*) of the Mandrin E points and micro/nanopoints indicate that they are statistically different between their morphology ($P < 2.2 \times 10^{-16}$ and $P < 0.05$). By comparing ethnographic or experimental control weapons with Mandrin E, one TCSA value appears to not be different. Mandrin E point TCSAs are not statistically significantly different from ethnographic spear-thrower dart tip values from Shea ($P = 0.09$) or experimental spear-thrower dart tips from Initiarc ($P = 0.67$) of which the last two do not differ each other significantly ($P = 0.317$; Fig. 9 and Table 1). Within Mandrin E micro/nanopoints, the TCSA values are all significantly different from the TCSAs of ethnographic or experimental controls. Once Mandrin

Fig. 5. Mandrin E DIFs on distal ends of archaeological points, micropoints, and nanopoints from Mandrin Layer E due to percussive actions (scale in millimeters). (**A**) Point. (**B**) Point. (**C**) Nanopoint. (**D**) Point. (**E**) Micropoint. (**F**) Nanopoint. (**G**) Point. (**H**) Point. (**I**) Micropoint. (**J**) point. (**K**) Point. (**L**) Point.

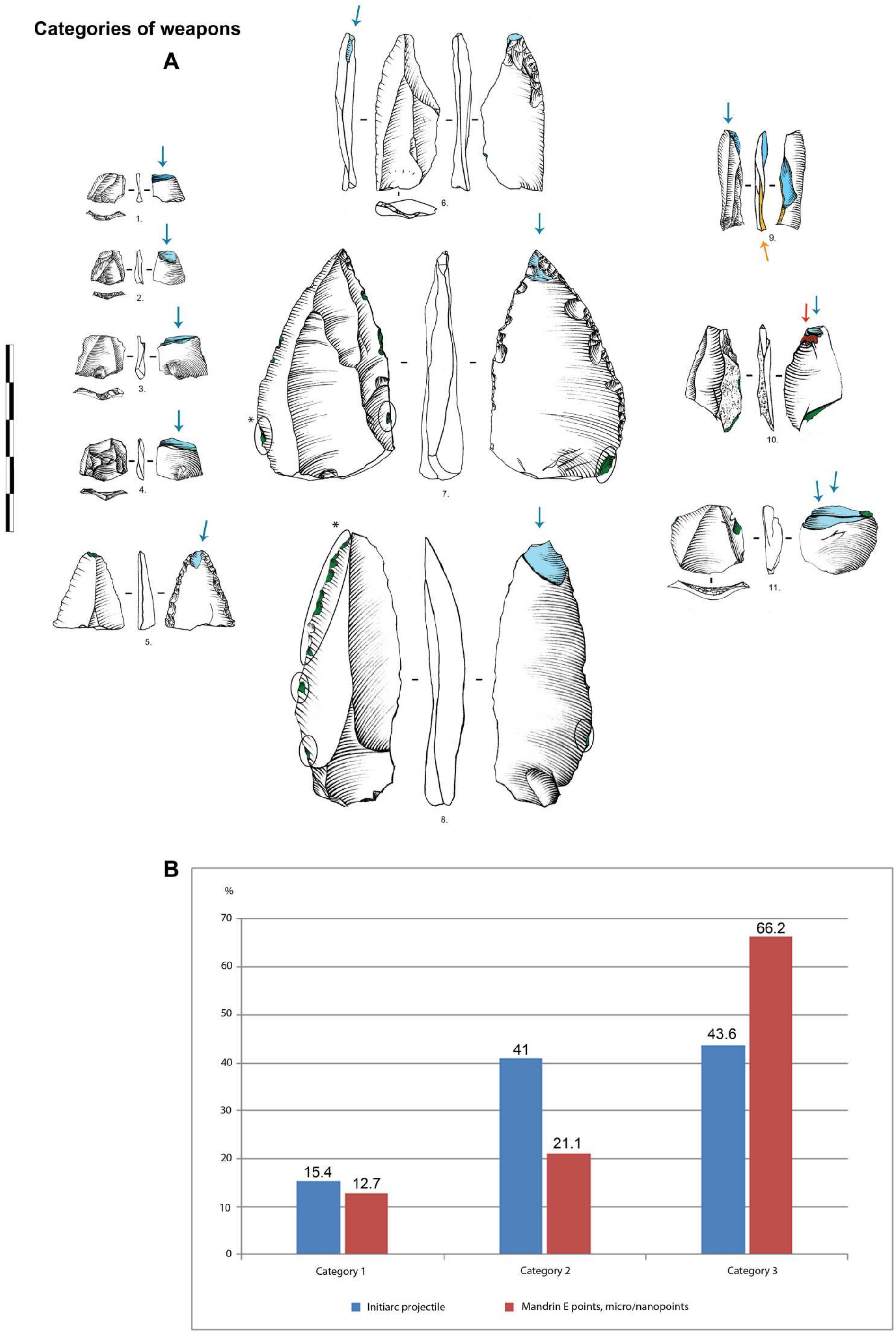

Fig. 6. Mandrin E DIFs on points, micropoints, and nanopoints associated with the different types of bending fractures. (**A**) (1 to 8) Category 3 weapons. (1 to 4) Nanopoints, (5) distal fragment of Soyons point, (6) Soyons point, (7) Soyons point, and (8) point. (9 to 11) Category 2 weapons. (9) Elongated micropoint, (10) proximal part of appointed point, and (11) proximal point fragment. (12 and 13) Category 1 weapons. (12) Retouched point and (13) point. (**B**) Histogram of the percentage of experimental and archaeological points within each category.

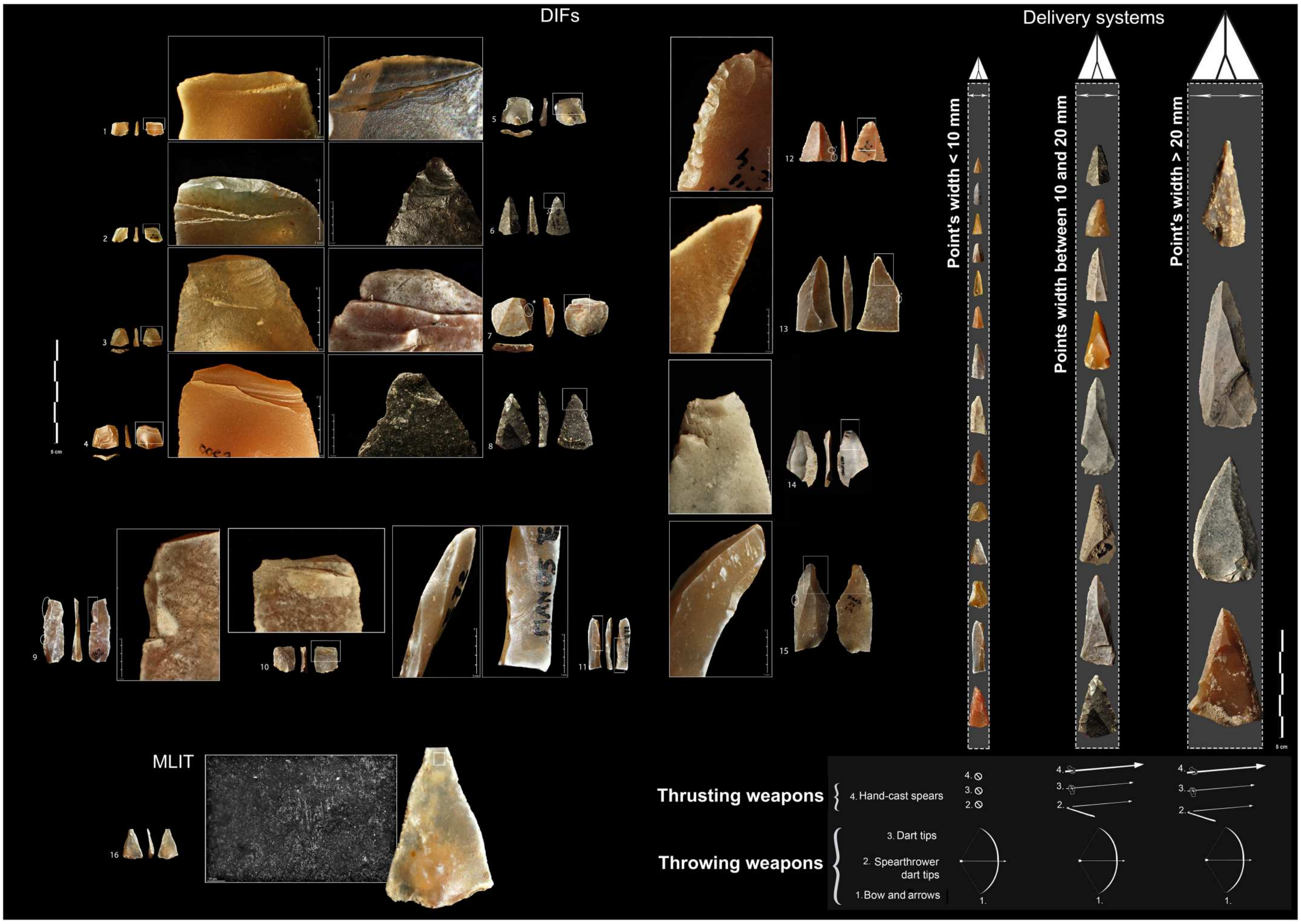

Fig. 7. Categories of points from Mandrin Layer E recording DIFs. (1 to 5) Nanopoints, (6, 8, and 13) distal points fragments, (7) proximal point fragment, (9 to 11) elongated micropoint, (12) distal fragment of Soyons point, (14) proximal part of appointed point, (15) Soyons point. Microscopic linear impact traces (MLIT): (16) nanopoint with an MLIT. Possible delivery systems according to point width when points are distally hafted.

E micropoints (n = 49) and nanopoints (n = 37) are differentiated, we get different statistical results. About the nanopoints, the mean TCSA [mean = 15.77 (12.9)] is below all other TCSA means of ethnographic or experimental stone controls and does not find any statistical match with any other TCSA controls [Fig. 9, Table 1, tables S2 to S4, and note S4 (TCSA statistics)].

By integrating recent data on ethnohistorical poisoned bone arrowheads from southern Africa (*35*–*38*), it appears that the TCSA values of the poisoned arrowheads and the Mandrin E nanopoints are not statistically significantly different ($P = 0.1321$, $P > 0.05$; table S3). It is important to mention that these poisoned arrowheads are bone points and not flint. Nevertheless, these comparative results show that the 37 nanopoints of Mandrin's Level E have mean TCSA values closer to poisoned arrowheads than to any other archaeological, experimental, or ethnographic stone point controls (table S4). In terms of TCSA, Mandrin's Neronian points fall directly in the spear-thrower range, while micropoints fall among bow-and-arrow technologies.

These results give solid evidence of the use of the bow and arrow within the smallest Neronian points, while the largest Mandrin E points show TCSAs compatible with their delivery using a spear-thrower, but these large points could ballistically be also delivered by bow. The specific weapon delivery system of the larger points could not be defined and should then be considered as "weapon components/tips" (*39*).

More generally in sub-Saharan Africa, there is strong evidence for the combination of bow and javelin hunting by 70 to 58 ka ago (*39*), but it seems more complex for the use of spear-thrower-and-dart. Several hypotheses have been proposed to explain the lack of evidence for spear-thrower-and-dart usage: Either they never existed, or they were used and then abandoned, or dart hunting was developed before or alongside bow hunting, but problems of preservation and archaeological methods prevented the detection of such use (*39*). A bow is undoubtedly more precise and easier to use, easier to learn, and the effort less intense and less violent compared to a dart (*25*, *40*). Easy to carry on the back, the bow can be used in open or closed environments, on land or in water, and is equally effective in stalking, alone or in a group hunt (*41*, *42*, *43*, *44*). The arrow, although more difficult to make, is nevertheless extremely fast, usable at great distance (up to 100 m) and easily

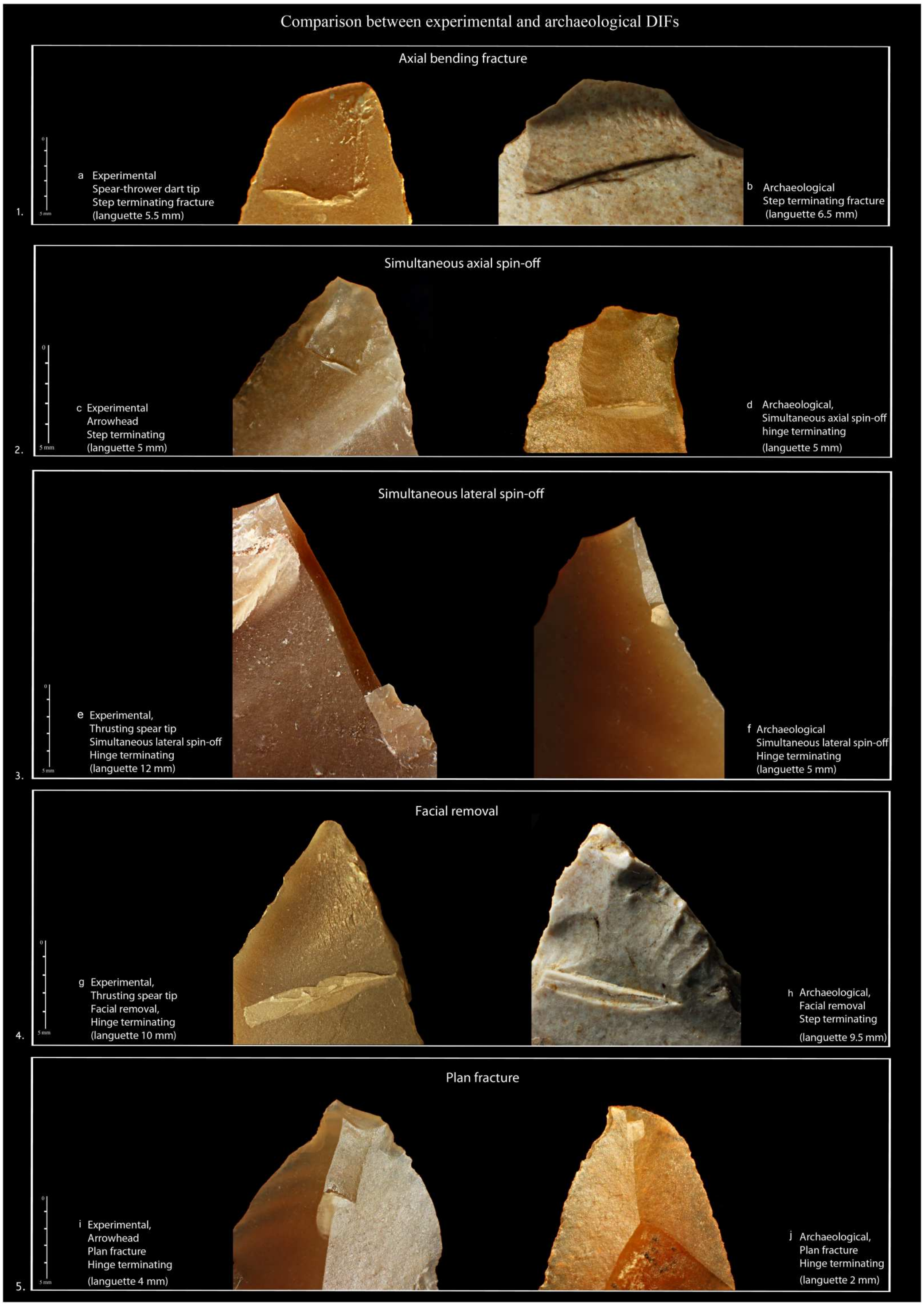

Fig. 8. Comparison between experimental and archaeological DIFs. 1. Axial bending fracture. 2. Simultaneous axial spin-off. 3. Simultaneous lateral spin-off. 4. Facial removal. 5. Plan fracture.

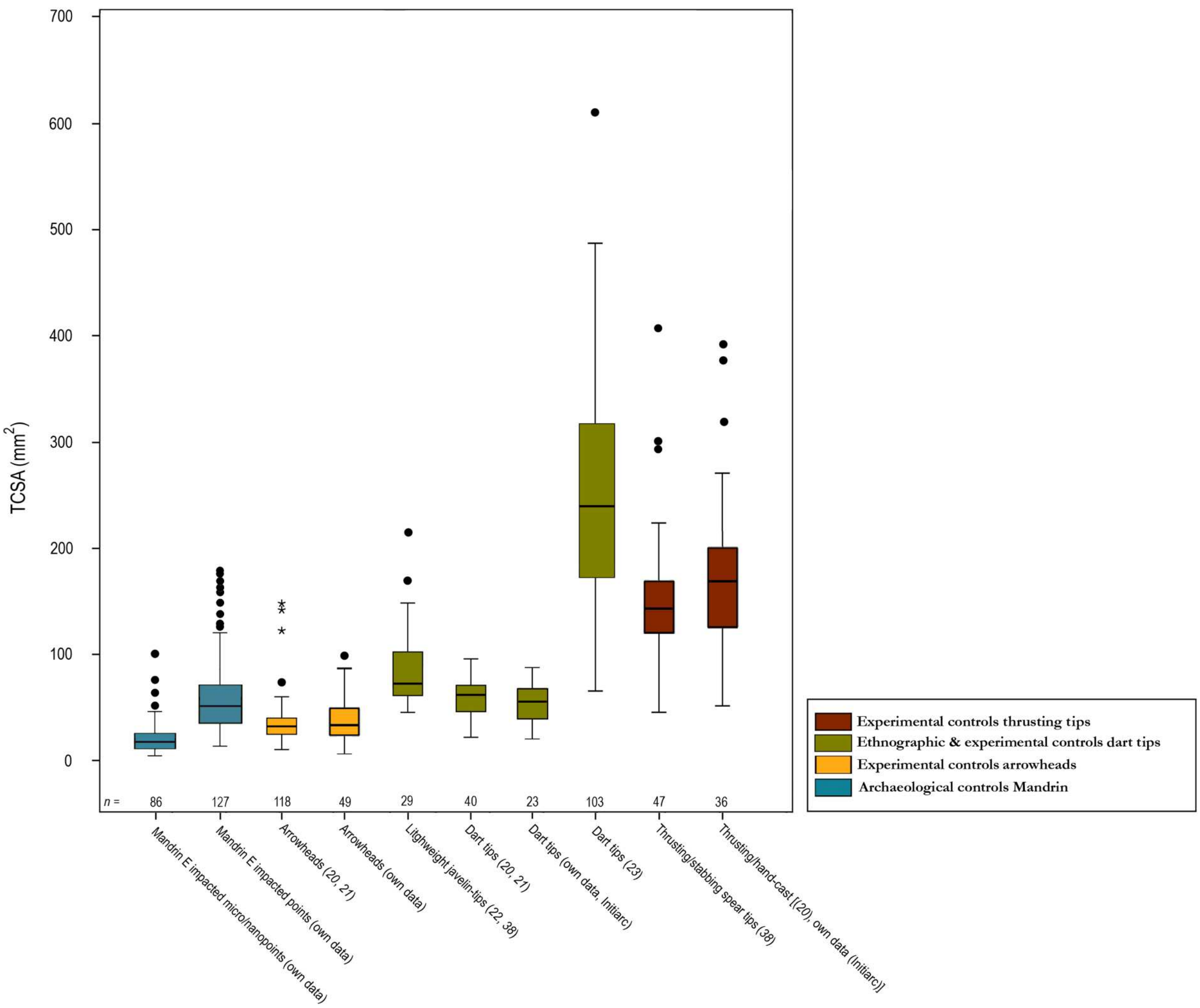

Fig. 9. Comparison of ethnographic and experimental TCSA with Mandrin E points and micro/nanopoints (*20*–*23*, *38*).

transportable in a quiver (*45*). Hunting strategies based on the combination of bow and spear-thrower are also well represented in the ethnographic record and may represent a plausible explanation for the presence of very distinct categories of points used as weapons in the Neronian.

DISCUSSION

Mechanically projected weapons represent one of the most distinctive technical features of all Eurasian UP cultures, distinguishing them from any MP ones (*1*–*3*, *7*, *20*, *46*–*47*). At Mandrin, functional analyses of all the MP layers before and after Layer E demonstrate a lack of the advanced technologies documented in Layer E. In carrying out a functional study of the entire Mandrin sequence, distinct realities have emerged concerning weaponry. Despite very comparable types of installation, faunas that are globally identical in their representations and uses, and a more or less similar number of blanks within each of the layers of the sequence, the results show a remarkably asymmetrical distribution of the representation of affected blanks [fig. S2 and note S3 (Archaeological results)].

The Rhône Valley is the most important natural corridor linking the Mediterranean Basin with the Northern European steppes and records an early exploration into Western Europe by modern humans who did not lead to their permanent presence, which would only be established 10 to 12 millennia later (*4*). We document here that this earliest migration of humans into Neanderthal territories is associated with the mastery of bow. We also show that these highly controlled technologies were unknown locally among Neanderthals groups like elsewhere in Eurasia. The use of these advanced technologies may be of crucial importance in the understanding of the remarkable expansion of the modern populations.

Bow technologies can easily remain below archaeological visibility. This is the case during most of the Eurasian UP, where mechanically projected weapons are widely accepted, but where the archaeological distinction between spear-thrower dart tips and arrowheads is constrained by the presence of laterally hafted elements (commonly tiny backed bladelets) or larger pointed implements, which both can indistinctively be propelled by bow or spear-thrower (Fig. 9 and Table 1) (*9*, *20*, *38*). In these circumstances, spear-thrower interpretation remains a minimal proposition

Table 1. TCSA values and statistical results for archaeological, experimental, and ethnographic points.

	n	Min	Max	Mean (SD)	Median (IIQ)	Versus Mandrin points	Versus Mandrin micro/nanopoints	Source
Mandrin points	127	12	175	56.3 (34.7)	50 (33–70)	$<2.2 \times 10^{-16}$, $P < 0.05$		This study
Mandrin micro/nanopoints	86	3	98	19.5 (14.9)	16.50 (10–24)			This study
Ethnographic arrowheads	118	7.9	145.8	32.53 (20)	29.87 (22–38)	2.165×10^{-12}, $P < 0.05$	9.689×10^{-13}, $P < 0.05$	(*21*)
Experimental arrowheads	50	7	99	30.79 (19.8)	26.75 (16.5–40.4)	3697×10^{-8}, $P < 0.05$	0.0001, $P < 0.05$	This study
Experimental lightweight Javelin	29	47.5	216	89.72 (39.7)	75 (63–104)	1.528×10^{-16}, $P < 0.05$	8.118×10^{-15}, $P < 0.05$	(*22*, *38*)
Experimental dart tips	23	20	87.5	52.8 (20)	52.8 (37.5–64.5)	0.6669, $P > 0.05$*	3.81×10^{-10}, $P < 0.05$	This study
Ethnographic dart tips	40	20.3	94.3	57.9 (18)	60.3 (44.7–69.2)	0.09108, $P > 0.05$*	5.547×10^{-16}, $P < 0.05$	(*21*)
Ethnographic dart tips	103	66.6	488.4	240.02 (101.5)	240.7 (172.3–315.2)	$<2.2 \times 10^{-16}$, $P < 0.05$	$<2.2 \times 10^{16}$, $P < 0.05$	(*23*)
Experimental thrusting/hand-cast	36	50	392	165.8 (80.7)	148.5 (123.0–189)	6.53×10^{-15}, $P < 0.05$	$<2.2 \times 10^{16}$, $P < 0.05$	(*21*), This study
Experimental thrusting spear tips	47	46	406	153.9 (61.7)	143.5 (119.5–169)	$<2.2 \times 10^{16}$, $P < 0.05$	$<2.2 \times 10^{16}$, $P < 0.05$	(*38*)
	n	**Min**	**Max**	**Mean (SD)**	**Median (IIQ)**	***P* value**		
Mandrin micropoints	49	3.5	98	22.28 (15.8)	19 (15–27)	0.003, $P < 0.05$		
Mandrin nanopoints	37	3	72.5	15.77 (12.9)	12 (9–18)			

*There is no significant TCSA difference between ethnographical dart tips from Shea and experimental dart tips from Initiarc and Mandrin E points.

during most of the UP, whereas bow use in Eurasia is highly suspected at least as early as 25 to 37 ka ago (*48*, *49*).

If bow-and-arrow technologies are largely perceived as an emblematic step in technological innovation, it must be underlined that just as for the North European Late Paleolithic (*31*), Paleoindians (*50*), or historic Inuit populations (*51*), existing bow-and-arrow technologies may well have been ignored by neighboring groups, neglected, or relinquished at different moments of their technological history. This suggests that the success and spread of technological innovations are primarily constrained by social choices and not necessarily by the rational benefits offered by said innovations (*52*). This notion should continue to guide future research to a much-needed reexamination of the true complexity of behavioral and social evolution, where evolutionary steps and technological advantages can be thwarted by social choices and norms. Future research will aim to elucidate these complex interactions between humans and Neanderthals during this pivotal period in human evolution.

MATERIALS AND METHODS

The Mandrin E collection is a particularly well-preserved lithic industry. This preservation is due to a rapid sand deposition in the dry environment of the shelter, with no secondary displacement (*4*). Only chemical alterations, such as "gloss" and "white patina," affect several flints restricting a systematic microscopic use-wear analysis, a common feature in functional analysis, including recent prehistoric industries. Thankfully, this microscopic chemical alteration does not hinder the determination of weapons use, which depends mostly on macroscopic scar identifications.

Naked-eye observation of all the archaeological material from Mandrin E ($n = 2267$) was followed by a selection for macrofracture examination under macroscope (Leica Z16 APO, 0.57×, 6.3×) and analysis under microscope (Leica DMR, Leica DMLP, 100×, 200×). A wider use-wear analysis was developed on the other various categories of lithic elements of the archaeological collection, involving flakes, blades, bladelets, points, and micro/nanopoints, to enable a complete overview of the various activities recorded at the site and how they were eventually interfered to specific technical categories.

We first differentiated in our functional analysis "pressure motions" from "percussion motions" (*53*). Actions performed by pressure include longitudinal (sawing, cutting, and grooving), transversal (scraping), mixed (cutting and scraping, for example), or rotating movements (drilling; Fig. 3). These modes of action are related with domestic activities such as butchering, skin treatment, woodworking, etc. Motions related to percussion include throwing or thrust actions, and they are related to cinegetic activities (e.g., hunting or war).

Our method is based on a multitude of studies about archaeological stone weapon recognition (*9*–*22*, *53*, *54*) and takes into account criticisms of the method (*55*–*58*) and improvement therein (*1*, *59*–*63*). Methodological weaknesses have been outlined (*58*), highlighting the main biases of much of the research on the concept of Paleolithic weapons. This study notes a simplification of the macrofracture method, a meager experimental base, poor identification of DIFs, poor representation of diagnostic elements within assemblages, and, within these small assemblages of suspected weapons, the recognition of a single DIF deemed diagnostic on each of the points involved. Some of the research asserts that it is the accumulation of different traces on the whole of an object (and not a single fracture, however characteristic it may be) that would justify its interpretation as a weapon (*64*–*66*). We agree with the authors that the accumulation of stigmata reinforces the diagnostic character, but there is nevertheless the risk here of an overly mechanical approach (note S3, Methods). These characteristics must additionally be connected to the morphological realities of the analyzed piece and thus to its potential, as a weapon and the frequency of affected pieces within the global corpus studied must be evaluated in parallel to test the coherence of the information highlighted on this piece. So, our study is therefore based on a classical use-wear analysis added to an analysis by combination of diagnostic characters. The first method consists in the study of the traces of wear along the edges in connection with the domestic sphere. As for the second method, it consists in approaching the pieces recording traces related to hunting or warlike activities, based on a combinatorial analysis of the DIFs attested on the same piece [Fig. 4 and note S3 (Methods)].

Potential DIFs are then compared to an experimental reference set to (i) distinguish taphonomic traces (e.g., those caused by trampling, knapping, or retouch rather than weapon use) (*55*–*57*) from those resulting from human use, (ii) distinguish damage from use as hunting weapons from those formed by other tasks such as cutting or scraping, and (iii) infer mode of weapon use, whether as a hand-held weapon (i.e., those used with a thrusting motion) or as a projectile, whether hand-thrown or by mechanical propulsion using a spear-thrower or bow (note S3, Projectile experimental results). Then, an object will be considered as a weapon tip only if the piece shows at least one DIF located on the tip, associated with other traces of use wear (lateral microtraces, hafting trace, etc.) and if the object is morphologically a potential component of a hunting weapon.

Diagnostic impact fractures

DIFs are specific categories of scars and macrofractures directly related with violent, axially oriented (hafted) impacts, first defined by the HoHo Committee (*54*) and thereafter universally used in projectile studies for the recognition of specific DIFs (*9*–*15*). We use here a variation of F. Fischer, M. O'Farrell, and H. Plisson and J.-M. Geneste's technical terminology (*9*, *10*, *12*, *13*). Each discriminating DIF must be considered in its eventual combination with other scars and their relationship with the specific piece's morphology and dimensions, especially when dealing with points from 8-mm to 8-cm maximum length. We consider here DIFs, or "complex fractures," lithic elements recording one or several of the following diagnostic bending features (Fig. 4A): (i) apical bending fractures with a step terminating fracture despite the extension's length; (ii) apical bending fractures with hinge and feather termination with a minimal length of an extension, lateral bending fracture with a minimal length of an extension, and plan fracture with a minimal length of an extension (at least 1.5 mm for micropoints, nanopoints, and bladelets and 2, 4, or 6 mm for points); (iii) an axial or lateral spin-off (burin-like spin-off) with an extension [same length criterion as (ii)] (*20*), any microscopic linear impact traces (MLIT) (Fig. 7, no. 16, and fig. S5, nos. 4 to 6) (*9*, *10*, *13*, *15*, *67*).

When fractures present an extension, a minimal length must be defined to determine their value as a diagnostic criterion. In function of the technical context, this minimal length has been placed between 1.5 and 3 mm, at 2 mm (*12*), or from 4 to 5 mm and to 6 mm concerning heavy hand-cast spears (*53*). The variations of the fracture (languet, literally, "tongue") length are directly related with the specific dimensions of the artifact under study and its uses in the past. Heavy MP pointed weapons' stigmata cannot be directly compared with those on the tiny bladelets of an Aurignacian context. There is a link, in terms of volume, length or mass, between these artifacts that easily pass a ratio of 1 for 10 in terms of length, thickness, or mass. In Mandrin E, both points and especially micro/nanopoints are incomparably tinier than the classic MP pointed tools.

TCSA statistics

Mass or distal tip penetrating angles are potential ballistic indicators (*68*), but these measurements can only be considered on complete specimens. Experimental and archaeological diagnostic projectile fractures commonly remove the distal tip. These fractures also affect the measurable mass of the broken projectile. Concerning tip angles, archaeological and ethnographic data demonstrate a large diversity of technical solutions for weapon making and show that tip angles do not correspond to an effective ballistic criterion (*13*, *16*, *18*, *19*). This is because the distal part of a shaft can be armed, and highly effective, with tangentially (rather than distally) hafted elements ("armatures tranchantes"). This illustrates a non-diagnostic effect of the distal tip penetrating angle as a ballistic tool for weaponry identification.

By identified TCSA, Hughes (*35*) used width and thickness measurements as an effective discriminator of different functional classes of lithic weapon armatures. The TCSA is a morphological index used as a ballistic indicator for lithic points that some scholars link to their specific delivery systems (bow, spear-thrower, or hand-cast spears) (*20*, *21*, *34*), although the reliability of this measure is discussed by some authors [e.g. (*63*)].

We restate here that the TCSA metric is used in our work only to provide a general assessment of probable use in the past through more formal statistical comparisons of archaeological, experimental, and ethnographic sample means and variance in TCSA values (*20*–*23*, *36*–*38*) and not a demonstration method to determine the delivery systems used for Mandrin weapon tips.

In Mandrin E, TCSA was established on the points for which their engagement in percussive actions was determined. TCSA was calculated on the basis of the full points and fragmented points for which the maximum width and thickness are known (n = 213; Fig. 9, Table 1, and tables S2 to S4).

Supplementary Materials

This PDF file includes:
Supplementary Text
Notes S1 to S4
Figs. S1 to S6
Tables S1 to S5
References

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