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RESEARCH

Testing tools: an experimental investigation into technical and economic aspects of Levantine rock art production

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Abstract
For over a century, scholars have presented several proposals regarding the paint application tools used to create Levantine rock art. However, such proposals have largely rested on theoretical assumptions and inductive inferences that have not been rigorously tested. In this experimental investigation, we compiled these hypotheses and crafted 60 tools that were tested through systematic experiments to assess their performance and technical affordances for the creation of images with techno-visual features equivalent to those of the Levantine paintings. These experiments allowed us to obtain analytical parameters with independent validation, which were used as diagnostic criteria to analyse the rock art from nine sites located in eastern Spain. Results reveal that out of 60 tools, only 10 –five hair brushes, three plant brushes, and two feather brushes–afforded the production of images with techno-visual features highly similar to those of the archaeological paintings. Subsequently, we employed these tools to paint 10 full-size replicas of Levantine motifs, aiming to explore their potential role in the toolkit of prehistoric painters. Drawing on the data from both the systematic and the replicative experiments, and taking into account the level of labour investment required by the technical operations that permeate the production of the paint application tools, we suggest that Levantine technology was not based on an economic logic aimed at minimizing the costs associated with producing the images, but rather on a perspective where the priority was creating paintings with specific techno-visual qualities that reinforced the information transmitted through the graphic code.

Keywords Levantine rock art · Paint application tools · Experimental Archaeology · Technology

Introduction

Since the latter decades of the nineteenth century, archaeologists have been fascinated and intrigued by the paint application tools used in the production of prehistoric images. Marcelino Sanz de Sautuola (1880: 16), for example, emphasised the precision of the tools employed to create the Palaeolithic bisons of Altamira, as well as the outstanding technical skill of the Magdalenian painters. Although this and other initial remarks were mainly based on general observations of the rock art motifs, the development of experimental archaeology from the 1970s onwards allowed some scholars to investigate this issue from a deeper empirical standpoint (e.g. Couraud 1976; Pérez-Seoane 1988; Lorblanchet 1991), yielding important insights into the tools and techniques employed in the production of the

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paintings. However, in Europe, the research on the subject has remained restricted to an exploratory level, and there is still a lack of systematic experimental studies concerning the paint application tools used in Palaeolithic and post-Palaeolithic periods.

Thus, in this article, we present an experimental research on the paint application tools used in the production of Levantine rock art (LRA), the visual expression of a post-Palaeolithic cultural tradition that emerged and flourished in eastern Spain. As part of an extensive experimental programme aimed at reconstructing the LRA *chaîne opératoire* (Santos da Rosa 2019a; Santos da Rosa et al. 2023), we compiled all hypotheses proposed over more than a century of studies and crafted 60 experimental tools, which were systematically tested to evaluate their performance and to assess the level of correlation between the morphology of their active zones and the morphology of the experimental marks produced through their use. These experiments allowed us to obtain analytical parameters with independent validation that were used as diagnostic criteria to study the LRA of nine sites and to identify which tools produce experimental rock art marks with techno-visual features most similar to Levantine paintings. In a subsequent phase of this study, we employed the tools classified as the most analogous to the prehistoric ones to create 10 full-size replicas of LRA motifs, aiming to investigate their potential role in the toolkit of Levantine painters. Drawing on the data from both the systematic and the replicative experiments, and taking into account the labour investment required by the technical operations that permeate the production of the paint application tools, we formulate a series of empirically supported inferences concerning technical and economic aspects of LRA technology.

The Levantine paint application tools: over a century of controversy

Identified in nearly a thousand shelters distributed across Mediterranean Spain, LRA is renowned for its depictions of hunting, food gathering, dances and conflicts, made through the use of thin lines and different surface treatments in red, black, and white (López-Montalvo 2018; Rubio et al. 2019; Santos da Rosa et al. 2021a, b; Fernández Macías et al. 2023). The chronology of this artistic tradition has been a matter of debate since its academic discovery in the early twentieth century, and currently, researchers still discuss whether the origins of LRA date back to the Epipalaeolithic/Mesolithic (Viñas et al. 2016; Ruiz et al. 2022) or the Neolithic (Hernández Pérez 2012; Villaverde et al. 2012). In this context, although the technological aspects of LRA have been treated as a marginal topic throughout the history of research, scholars always exhibited a particular interest in the continuous and precise lines used to create the images (Fig. 1), and occasionally have engaged in meticulous examinations of these elements (Porcar 1943). Such interest has led to several proposals concerning the paint application tools used by Levantine painters, which according to different researchers, could be hair brushes (animal or human hair inserted into a haft), plant brushes (a branch whose end is crushed and cut to obtain bristles with specific morphologies), plant fragments (branches or roots with a whittled point), feathers (used in their natural state), or feather brushes (an entire feather of a feather fragment inserted into a haft) (Table 1; for a detailed synthesis, see Santos da Rosa 2019b).

To succinctly illustrate this controversy, certain proposals warrant closer scrutiny. Grimal and Alonso (2001: 95), for instance, contended that the production of hair brushes is a laborious and time-consuming process that would be beyond the technical capabilities of prehistoric populations. Hence, based on non-systematic experiments –mentioned by Grimal (1991: 52), but whose data have never been published– these authors proposed that feathers were the only paint application tool used in the production of LRA, which led them to coin the popular term "*trazo de pluma levantino*" and to defend the idea that the lines observed in the archaeological paintings could not have been produced with any other type of tool (Grimal and Alonso 2001: 96). On the other hand, after producing replicas of two archers and one quadruped, Bea (2007: 8) considered plant brushes as effective paint application tools and pointed out that they could have been used in the same way as feathers or even hair brushes in the creation of Levantine images (Bea 2007:7–8). Adopting a similar perspective, Ruiz (2012) conducted a replicative non-systematic experiment with feathers and argued that this tool would have been widely employed in the production of LRA. According to this author, the diagnostic information could be found on the initial and final tips of the lines, areas in which the traces left by the feather would be more discernible. In this regard, rounded and elliptical shapes would frequently appear in the initial tips, while pointed shapes would be more common in their final tips (Ruiz 2012: 335). Furthermore, analysing photographs of Levantine motifs from the Sierra de las Cuerdas (Cuenca), Ruiz observed –in addition to traces presumably made with feathers– the presence of thin parallel lines (~ 0.2 mm wide) that he interpreted as marks left by a hair brush (Ruiz 2012: 337).

Building on this background, it is possible to note that the aforementioned proposals are mainly based on theoretical assumptions, superficial observations, and the results of non-systematic replicative experiments in which the causal relationship between different variables was not properly taken into account. Concerning the latter, there is a lack of precise information about the experimental protocols employed in these studies, as well as the methods researchers used to

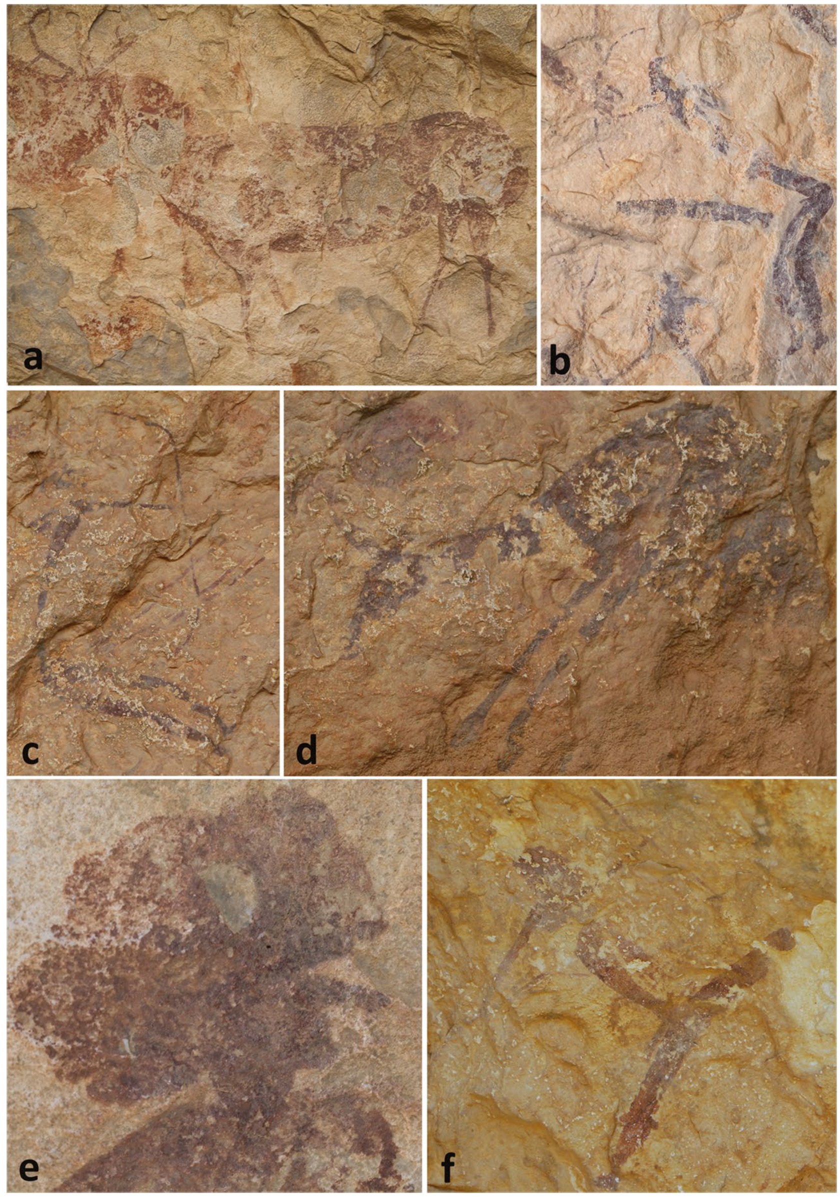

Fig. 1 Example of LRA and its technical aspects: a and e) Cova dels Rossegadors (Photo: A. Rubio); b) Cova del Civil (Photo: A. Rubio); c and d) Cova dels Cavalls (Photo: N. Santos da Rosa); e) Abric del Mas d'en Josep (Photo: N. Santos da Rosa). All the motifs shown in this figure come from the sites that comprise our archaeological study sample

address the technical variability in tool performance and results potentially influenced by chance. This implies that, even after more than a century, the hypotheses regarding the paint application tools used in the production of LRA still need to be rigorously tested.

Theoretical framework: performances, affordances and labour investment in producing and using paint application tools

Over the past five decades, experimental archaeology has proved to be an invaluable tool in testing hypotheses concerning the production of rock art paintings (e.g., Couraud 1988; Paunero 1992; Blanco and Barreto 2016; d'Errico et al. 2016; López-Montalvo 2017; Landino et al. 2023; Ozán et al. 2023; Santos da Rosa et al. 2023) and engravings (e.g. Bard and Busby 1974; Bednarik 1998; Keyser and Rabiega 1999; Álvarez and Fiore 1995; Álvarez et al. 2001; Santos da Rosa 2012; Santos da Rosa et al. 2014; Vergara and Troncoso 2015; Zotkina and Davydov 2022) in sites from diverse chronological periods and geographic areas.

This experimental approach is particularly significant in the context of a theoretical and methodological framework that aims to explore rock art's materiality through the study of technological processes and economic factors that permeate the creation of the images (Fiore 2007, 2009, 2018; Santos da Rosa 2019c). According to this perspective, the materiality of rock art is not limited to the components used

Table 1 Proposals concerning the paint application tools used by the Levantine painters

Paint application tool	Bibliographic reference	Criteria
Hair brushes	Hernández-Pacheco (1918: 67); Obermaier and Breuil (1927: 514); Obermaier (1938: 115); Almagro Basch (1949: 103); Beltrán Martínez (1968: 27); Utrilla (2000: 34); Sanchidrián Torti (2001: 382); Domingo Sanz (2012: 121); Viñas (2014: 690)	theoretical
	Bea (2007: 7–8)	non-systematic experiments
	Gavira et al. (2008: 54); Ruiz (2012: 338)	analysis of photographs
Plant brushes	Domingo Sanz (2012: 121); Viñas (2014: 690)	theoretical
	Bea (2007: 7–8)	non-systematic experiments
Plant fragments	Obermaier and Breuil (1927: 514); Utrilla (2000: 34)	theoretical
	Bea (2007: 7–8)	non-systematic experiments
Feathers	Beltrán (1968: 27); Alonso and Grimal (1989: 18); Utrilla (2000: 34); Sanchidrián Torti (2001: 382)	theoretical
	Porcar et al. (1935: 66); Grimal (1991: 52); Grimal and Alonso (2001: 95); Bea (2007: 7); Ruiz (2012: 333)	non-systematic experiments
	Gavira et al. (2008: 54); Ruiz (2012: 333)	analysis of photographs
Feather brushes	Obermaier and Breuil (1927: 514); Ripoll (1990: 72); Viñas (2014: 690)	theoretical
	Obermaier (1938: 115–116)	non-systematic experiments

in its production but also encompasses the performance and affordances of these elements, which are activated through human agency. Thus, in this article, we begin by exploring the concept of performance, here defined as the efficiency of the paint application tools in producing images with specific technical features. Subsequently, we employ the concept of techno-visual affordances (sensu Fiore 2020), which in this study pertains to the production and perception of the visual qualities of rock art motifs painted on a rocky surface.

In this context, we consider that the visual qualities of a rock art painting result from the use of tools, pigments, supports, and techniques, and from the combination of their performances and affordances via human labour to create the forms, colours, and textures of the artwork (Fiore 2020). Afforded by the technical means employed to produce the image, these techno-visual qualities emerge from the painting's materiality to evoke specific visual perceptions in those who observe the motifs and to complement the information transmitted through the graphic code. In the words of British anthropologist Alfred Gell, this is where the *"enchantment of technology"* resides: it allows people to *"make what is out of what is not"* (Gell 1994).

Furthermore, given that the tool's performance and techno-visual affordances are activated through a work process, we also adopt the concept of labour investment (sensu Fiore 2007) in an attempt to qualitatively assess the role of aspects such as time, energy, and skill in the production of paint application tools and their use in creating Levantine images. Shedding light on the making process within and beyond the practical operations, the use of this concept provides us with a better understanding of the cost and complexity of certain activities carried out by prehistoric painters, and contributes to deconstructing misconceptions about the technical and economic dimensions of technological processes developed in the past.

Materials and methods

In order to systematically study the performances and affordances of the experimental paint application tools, we designed an experimental protocol comprising seven stages: 1) procurement of raw materials in the study area; 2) production of experimental paint application tools; 3) systematic testing of the experimental tools; 4) evaluation of the experimental tools' efficiency; 5) analysis of the correlation between tools' active zones and the morphology of the line tips; 6) application of the experimental criteria to a LRA sample; and 7) creation of full-size replicas of Levantine motifs.

Procurement of raw materials

To craft the experimental tools, we selected raw materials that were available in the study area during the Mesolithic and Neolithic periods. To produce the hair brushes, we gathered guard hairs of bull (*Bos taurus*), goat (*Capra hircus*), deer (*Cervus elaphus*), rabbit (*Oryctolagus cuniculus)*, boar (*Sus scrofa*), and fox (*Vulpes vulpes*), as well as human scalp hair. This choice is justified by the presence of these animals in the zooarchaeological record of Cova Fosca (Olària 1988), a Mesolithic/Neolithic site located at the heart of the study area and just 1 km from Cova Remígia and Cingle de la Mola Remígia. Furthermore, this selection allowed us to examine the influence of hair texture and flexibility on the tool performance, given that bull, rabbit, fox and human hairs tend to be smooth and flexible, while goat, deer and boar hairs are coarse and more rigid.

To create paint application tools from plants, we collected fresh branches of hazel (*Corylus avellana*), lentisk (*Pistacia lentiscus*), lesser bulrush (*Typha angustifolia*), rush (*Juncus subulatus*), kermes oak (*Quercus coccifera*), and Mediterranean spurge (*Euphorbia characias*), as well as a dry branch of reed (*Phragmites communis*) and a root of mallow (*Malva silvestris*). To carry out this procedure, we relied on information from the archaeological context of the study area (Antolín et al. 2010) and the collaboration of Prof. Francesc Burjachs (IPHES – Rovira i Virgili University), a leading expert on the paleoenvironment of Mediterranean Spain. Employing such resources, it was possible to test whether tools crafted from woody (hazel, lentisk, kermes oak, and dry reed), fibrous (rush, Mediterranean spurge, and mallow) and spongy plants (lesser bulrush) exhibit significant variations in terms of efficiency.

We also gathered flight feathers and tail feathers of crow (*Corvus corax*), rock dove (*Columba livia*), and Spanish sparrow (*Passer hispaniolensis*), which allowed us to test the performance of feathers from birds of large, medium, and small sizes. In this sense, it should be noted that remains of *Corvus sp.* and *Columba sp.* were identified in the aforementioned zooarchaeological record of Cova Fosca (Olària 1988), and that the Spanish sparrow is an autochthonous bird of the Mediterranean region that was present in the study area in prehistoric times (Ericson et al. 1997).

Finally, we collected dry reed branches to be used as hafts, Aleppo pine resin (*Pinus halepensis*) to be employed as an adhesive, grasses to tie the hairs used in the brushes (*Brachypodium phoenicoides*), flint flakes for cutting and shaping some of the raw materials, hammerstones to crush the active zone of plant brushes and to grind mineral pigments, red ochre and binders (water and honey) to produce red paint, as well as natural limestone slabs with geological and topographic features equivalent to the walls of Levantine shelters. As for the latter, special attention was given to selecting flat supports without pronounced concavities or convexities and as similar as possible to each other, so that any micro-topographic differences between them would not generate biases in the experimental results. This implies that in all the experiments conducted, the interaction between paint and support in terms of fixation and absorption remained constant, while the interaction between tool and support varied based on the level of adaptability to the rocky surface exhibited by each tool – such variations were part of the results observed and recorded in our experimental protocol.

Production of experimental paint application tools

Employing the raw materials described in the previous section, we crafted 21 hair brushes, 12 plant brushes, 8 plant fragments, and 6 feather brushes. The experimental set was completed with 6 feathers and 7 feather fragments, culminating in a total of 60 paint application tools (Fig. 2; for details on the production of each tool, see Supplementary Material – Sect. "1"). To test a wider range of technical possibilities, the bristles of hair and plant brushes were shaped into three distinct active zone morphologies: pointed (p.a.z), convex (c.a.z), and flat (f.a.z). Conversely, feather brushes and feather fragments were crafted only with pointed and convex active zones, as the rachis precludes the use of a flat end.

Systematic testing of the experimental paint application tools

To evaluate the efficiency of the experimental tools, we painted with each tool five straight lines (6 cm long) and five curved lines (8 cm long) on vertically positioned limestone slabs, which resulted in a total of 600 lines (300 straight and 300 curved) (Fig. 3; see all lines in Santos da Rosa 2019a). The production of such experimental marks was carried out through single and continuous gestures from top to bottom, and aimed at creating a set of highly comparable images to assess the efficiency of the tools. Also, this procedure enabled the application of the resultant experimental parameters to the archaeological sample, as both straight and curved lines feature in all Levantine images. In this sense, the creation of five straight lines and five curved lines with each tool was intended to detect potential variability in their technical performance and to minimise the occurrence of results attributable to chance. In all cases, the experimental marks were produced using a red paint composed of 1 g of red ochre, plus 1 ml of water and 1 g of honey, a pictorial recipe experimentally tested and classified as highly similar to those used in the creation of LRA (Santos da Rosa et al. 2023). After their production, the experimental marks were stored vertically and left to dry for six months in a sheltered open-air space. This drying process was crucial to achieving a realistic view of the morphology and structural aspect of the lines, since the paint can exhibit slight shrinkage after being applied to the support due to evaporation of the water used as one of the binders.

In this context, it is noteworthy that to ensure the morphology of the experimental marks was not biased by the technical skill of the experimenter (NSR; 14 years of practical experience in the experimental study of rock art paintings and engravings), we conducted a pilot experiment where all tools were also used by one of the co-authors of this article (RV), who is not only an archaeologist but also

Fig. 2 The 60 experimental paint application tools produced and used in the present study

a professional painter with more than 50 years of experience in producing rock art replicas. Therefore, the official experiments were conducted only when the lines painted by both the experimenter and the professional painter exhibited identical morphologies, reflecting the maximum performance of the paint application tools.

Evaluation of experimental tools' efficiency

To assess the efficiency of the paint application tools, we analysed the causal relationship between three independent variables –tool category, tool raw material and morphology of the active zone– and three dependent variables: a)

Fig. 3 Systematic testing of experimental paint application tools

precision –the tool's ability to produce experimental marks with linear lateral edges; b) adaptability to the support surface –the tool's ability to adapt to the irregularities of the support and produce a uniform paint layer; and c) paint load capacity –the tool's ability to retain paint on its active zone and deposit it on the support allowing for the creation of continuous lines. The performance of each tool concerning these attributes was scored on a scale from 0 (poorest performance) to 10 (optimal performance) (see Supplementary Material – Sects. "2, 3, 4 and 5"). Subsequently, the scores obtained for each dependent variable were used to calculate the Efficiency Index (EI) of each experimental tool according to the following weighted average formula:

$$Ei = (W\mathrm{P} \cdot Pi) + (W\mathrm{A} \cdot Ai) + (W\mathrm{PL} \cdot PLi)$$

where:

- Ei represents the EI of the experimental tool i.
- $W\mathrm{P}$ is the weight attributed to the precision.
- Pi is the precision score of the tool i.
- $W\mathrm{A}$ is the weight attributed to the adaptability to the support surface.
- Ai is the adaptability to the support surface score of the tool i.
- $W\mathrm{PL}$ is the weight attributed to the paint load capacity.
- PLi is the paint load capacity score of the tool i.

Each weight reflects the relative importance of the corresponding dependent variable in determining the overall efficiency of the tool. In this regard, given that precision is paramount for producing well-defined lines and painting small details, it was assigned a weight of 0.5. This higher weight, compared to the other two technical features, is justified by the fact that issues related to the tool's inherent precision cannot be compensated by the technical skill of the painter or by the repeated execution of the technical operation, since attempts to retouch parts of the line's lateral edges to correct errors tend to alter its thickness, making it necessary to repaint the entire element to maintain the correct proportions. Adaptability, in turn, is directly related to the appearance of the paint layer and the internal structure of the lines. Despite its significance, the low adaptability of a tool can be compensated by repainting flaws in the structure of the painted elements. However, such correction demands a very high level of technical skill and labour investment and tends to be applicable only to lines that are 2 mm wide, or thicker. For this reason, a weight of 0.3 has been attributed to this variable. Finally, the paint load capacity determines how much a tool can be used before it runs out of paint in its active zone. A suboptimal performance in this aspect can be mitigated by the successive repetition of the technical operation, namely, the creation of several short linear strokes to form a longer continuous line. Given that this process does not require a high level of technical expertise or significant labour investment, a weight of 0.2 has been assigned to this technical feature. Thus, taking into account these different weights, the formula for calculating the EI was devised as follows:

$$Ei = (0.5 \cdot Pi) + (0.3 \cdot Ai) + (0.2 \cdot PLi)$$

Assessment of the correlation between the morphology of the tool's active zone and the morphology of the line tips

To test the assumption that the morphology of the line tips tends to reflect the morphology of the tool's active zone, we examined 1200 tips of the 600 straight and curved lines and classified them as pointed, convex, flat or irregular. The data derived from this examination were used to ascertain, for each tool, a Correlation Index (CI) that spans from 0 to 5 and reflects the total number of initial or final tips whose morphology corresponds to that of the tool active zone (see Supplementary Material – Section "6"). Based on this classification, the level of correlation was rated as high (CI: 5), medium (CI: 3 – 4), low (CI: 1 – 2), or non-existent (CI: 0). Subsequently, we used these data to determine how frequently these different levels of correlation manifest in each tool category and in relation to the different types of active zones.

Application of the experimental criteria to the LRA sample

To identify the paint application tools potentially used in the production of the Levantine paintings, we applied the diagnostic criteria obtained through the development of the experimental protocol to an archaeological sample of nine sites located in the Maestrazgo region and surroundings (Fig. 4; see Supplementary Material – Sect. "7"). This selection was based on the fact that: the nine sites have been extensively studied, and there is a broad range of data about their paintings; b) the approximately 2.500 images documented in these shelters form a representative sample of the LRA, reflecting its technical, typological and thematic diversity; and c) several authors argue that the rock art represented in these sites is the result of a common technological tradition, socially transmitted over many generations (Obermaier 1938; Porcar 1945; Viñas 1982; Domingo Sanz 2012).

This application of the experimental criteria to the LRA sample implied a detailed comparison between each of the 600 experimental lines and the lines present in about 1,000 well-preserved rock art motifs from the selected sites (see Supplementary Material – Sect. "8"). The infeasibility of transporting dozens of heavy limestone slabs to the field for in-situ comparison led us to carry out this procedure through the use of high-resolution photographs. Hence, the lateral edges, the internal structure, and the initial and final tips of the experimental lines were compared to those of the lines used in outlining the archaeological images and depicting details such as bows, arrows, headdresses, body ornaments, and anatomical features in human and animal figure (Fig. 5), which generally exhibit the following characteristics: a) lateral edges that are either completely linear or slightly wavy in some of their sections, which never appear irregular or fragmented (except for taphonomic degradation) and never exhibit smudging or fine lines adjacent to the main one due to the splay of the brush bristles; b) a solid and essentially homogeneous internal structure, with a very low incidence of flaws in the paint layer (once again, except when the paintings are impacted by taphonomic processes); c) a width that tends to remain stable throughout the entire line; and d) initial and final tips with well-defined morphology. Within the scope of this comparison, each experimental line was evaluated and assigned a score reflecting its degree of similarity to the lines observed in the Levantine images. The aggregation of scores for the five lines painted with a particular tool culminated in the calculation of a Similarity Index (SI), which ranges from 0 (dissimilar) to 10 (highly similar) and indicates the overall degree of similarity between the experimental marks produced with the tool and the archaeological sample (see Supplementary Material – Sect. "9").

Production of full-size replicas of LRA motifs

After identifying the experimental tools that produce straight and curved lines with techno-visual features most similar to those of the Levantine paintings, we used them to create 10 full-size replicas of LRA motifs that are part

Fig. 4 Location of the nine rock art sites that comprise the study sample

Fig. 5 Example of comparison between experimental and archaeological lines

of the study sample and representative of this artistic tradition (Fig. 6; see Supplementary Material – Sect. "10"). This procedure aimed to ascertain the techno-visual affordance of these tools in outlining figures, infilling the bodies of human and animal motifs, and representing delicate anatomical details (antlers, hairs, hooves, etc.) as well as objects (bows, arrows, ropes, etc.). Furthermore, creating these replicas enabled us to observe the wear processes that occur when the different types of tools come into contact with the support surface, and to identify which of them could have their lifespan extended through maintenance and/or recycling procedures.

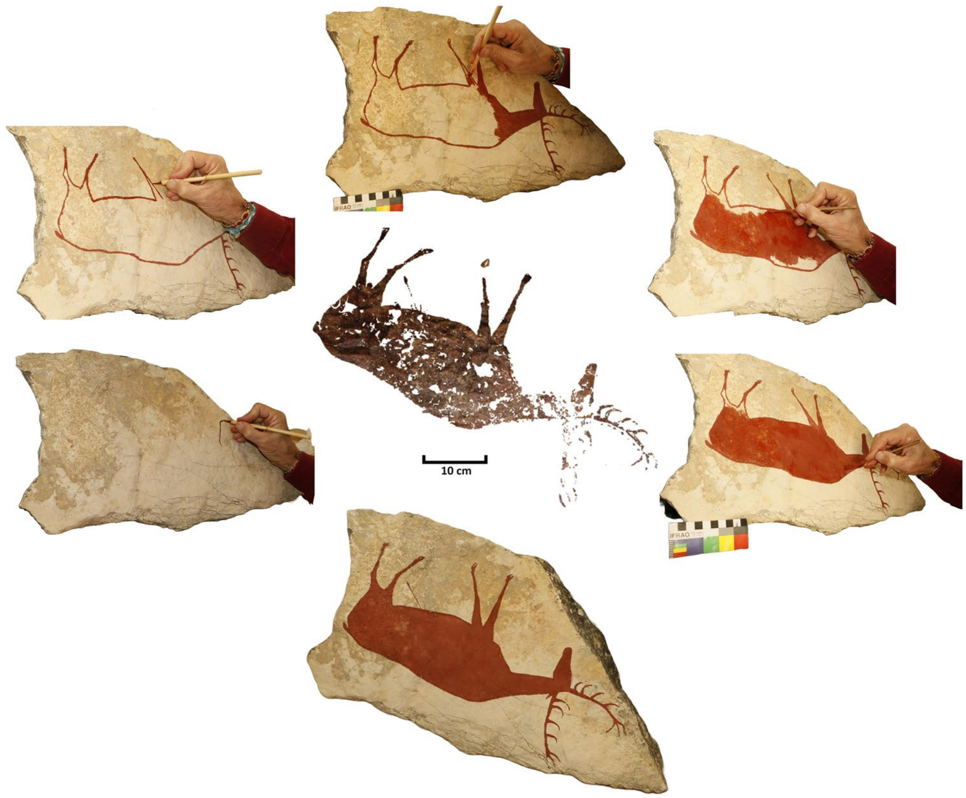

Fig. 6 Example of the LRA full-size replicas. Upside-down red deer from Cova Remígia (Digital tracing of the original rock art motif: López-Montalvo 2018: 213)

Experimental results

Assessing the efficiency of the experimental paint application tools

To assess the efficiency of the experimental paint application tools, their EIs were sorted from highest to lowest and divided into three performance levels (PL): a) High (EI: 8.0 – 10.0; ovr-EI: 16.0 – 20.0); Medium (EI: 5.0 – 7.9; ovr-EI: 10.0 – 15.9); and Low (EI: 0 – 4.9; ovr-EI: 0.0 – 9.9) (Tables 2, 3, 4, 5, 6, and 7). Based on this classification system, in the following pages we analyse the results of each tool category focusing on the tool's overall performance and their respective ovr-EIs, which correspond to the sum of the EIs obtained for producing straight and curved lines. Nonetheless, the performance of the tools when used for painting each of these two types of experimental marks can also be observed in the tables that summarize the data.

Thus, out of the 21 hair brushes, three exhibited a high PL (ovr-EI: 16.3 – 19), while the PL of 12 was rated as medium (ovr-EI: 10.3 – 15.6) and that of the remaining six as low (ovr-EI: 6.4 – 9.7) (Table 2). Bull, boar and human hair brushes proved to be the most suitable for the production of brushes, with bull hair yielding the best result due to its notable balance between texture and flexibility (Fig. 7a). Deer and goat hair brushes, in turn, exhibited intermediate performances, attributed to the more pronounced roughness of their textures (Fig. 7b). Finally, rabbit and fox hair brushes had lower efficiency due to their excessive softness and susceptibility to deformation when the tool encounters the irregularities of the support (Fig. 7c). Also, tools with pointed and flat active zones performed better than those with convex bristles. In this sense, it is worth noting that the efficiency of hair brushes is strongly dependent on the correct combination between the hair type and the morphology of the active zone. A clear example of this dependency can be found among the bull hair brushes. In this case, the tool with a p.a.z. reached an ovr-EI of 19.0, whereas those crafted with the same raw material but with convex and flat active zones exhibited ovr-EIs of 9.7 and 10.7, respectively.

Regarding the 12 plant brushes, eight exhibited a medium PL (ovr-EI: 10.0 – 15.5) and four a low PL (ovr-EI: 4.6 – 9.4) (Table 3). Among these tools, those crafted from rush and lesser bulrush (fibrous and spongy plants) showed a better performance and ranked in the upper half of the classification table (Fig. 7d). Conversely, those made from hazel and lentisk (woody plants) proved less efficient and fell within the lower half, mainly because the harder bristles of these brushes cause them to exhibit a more pronounced drop in performance when used to paint curves (Fig. 7e). Furthermore, it was observed that, as in the case of hair brushes, the efficiency of the tools is contingent upon the selection of an active zone morphology that is compatible

Table 2 Results of the efficiency analysis of hair brushes. Green: tools whose performance level was classified as High (EI: 8.0 – 10.0; ovr-EI: 16.0 – 20.0); Yellow: tools whose performance level was classified as Medium (EI: 5.0 – 7.9; ovr-EI: 10.0 – 15.9); Red: tools whose performance level was classified as Low (EI: 0 – 4.9; ovr-EI: 0.0 – 9.9)

Straight lines		Curved lines		Straight and curved lines	
Tool	EI	Tool	EI	Tool	Ovr EI
Bull hair brush – p.a.z.	9.5	Bull hair brush – p.a.z.	9.5	Bull hair brush – p.a.z.	19.0
Boar hair brush – f.a.z.	9.5	Boar hair brush – f.a.z.	7.8	Boar hair brush – f.a.z.	17.3
Human hair brush – p.a.z.	9.0	Human hair brush – p.a.z.	7.3	Human hair brush – p.a.z.	16.3
Deer hair brush – c.a.z.	9.0	Goat hair brush – f.a.z.	7.3	Deer hair brush – c.a.z.	15.6
Human hair brush – f.a.z.	8.5	Deer hair brush – c.a.z.	6.6	Goat hair brush – f.a.z.	14.4
Deer hair brush – f.a.z.	7.3	Rabbit hair brush – c.a.z.	6.6	Human hair brush – f.a.z.	12.9
Goat hair brush – f.a.z.	7.1	Human hair brush – c.a.z.	6.0	Boar hair brush – p.a.z.	12.3
Boar hair brush – p.a.z.	7.0	Fox hair brush – f.a.z.	6.0	Rabbit hair brush – c.a.z.	12.1
Goat hair brush – p.a.z.	6.7	Deer hair brush – p.a.z.	5.5	Deer hair brush – f.a.z.	11.9
Bull hair brush – f.a.z.	6.7	Boar hair brush – p.a.z.	5.3	Goat hair brush – p.a.z.	11.8
Bull hair brush – c.a.z.	6.4	Fox hair brush – p.a.z.	5.2	Fox hair brush – p.a.z.	11.2
Fox hair brush – p.a.z.	6.0	Goat hair brush – p.a.z.	5.1	Human hair brush – c.a.z.	11.1
Boar hair brush – c.a.z.	6.0	Rabbit hair brush – f.a.z.	4.9	Rabbit hair brush – f.a.z.	10.9
Rabbit hair brush – f.a.z.	6.0	Deer hair brush – f.a.z.	4.6	Bull hair brush – f.a.z.	10.7
Rabbit hair brush – c.a.z.	5.5	Human hair brush – f.a.z.	4.4	Fox hair brush – f.a.z.	10.3
Human hair brush – c.a.z.	5.1	Bull hair brush – f.a.z.	4.0	Bull hair brush – c.a.z.	9.7
Fox hair brush – f.a.z.	4.3	Goat hair brush – c.a.z.	3.8	Deer hair brush – p.a.z.	9.6
Rabbit hair brush – p.a.z.	4.2	Bull hair brush – c.a.z.	3.3	Boar hair brush – c.a.z.	8.3
Deer hair brush – p.a.z.	4.1	Fox hair brush – c.a.z.	2.5	Goat hair brush – c.a.z.	7.8
Fox hair brush – c.a.z.	4.1	Boar hair brush – c.a.z.	2.3	Fox hair brush – c.a.z.	6.6
Goat hair brush – c.a.z.	4.0	Rabbit hair brush – p.a.z.	2.2	Rabbit hair brush – p.a.z.	6.4

Table 3 Results of the efficiency analysis of plant brushes. Green: tools whose performance level was classified as High (EI: 8.0 – 10.0; ovr-EI: 16.0 – 20.0); Yellow: tools whose performance level was classified as Medium (EI: 5.0 – 7.9; ovr-EI: 10.0 – 15.9); Red: tools whose performance level was classified as Low (EI: 0 – 4.9; ovr-EI: 0.0 – 9.9)

Straight lines		Curved lines		Straight and curved lines	
Tool	EI	Tool	EI	Tool	Ovr EI
Hazel brush – c.a.z.	9.2	Rush brush – f.a.z.	7.5	Rush brush – f.a.z.	15.5
Rush brush – f.a.z.	8.0	Rush brush – c.a.z.	7.2	Rush brush – c.a.z.	14.7
L. bulrush brush – p.a.z.	7.5	L. bulrush brush – p.a.z.	6.0	L. bulrush brush – p.a.z.	13.5
Rush brush – c.a.z.	7.5	Rush brush – p.a.z.	5.5	Rush brush – p.a.z.	11.5
Hazel brush – p.a.z.	6.3	L. bulrush brush – f.a.z.	5.1	L. bulrush brush – c.a.z.	11.1
L. bulrush brush – c.a.z.	6.1	L. bulrush brush – c.a.z.	5.0	L. bulrush brush – f.a.z.	10.6
Rush brush – p.a.z.	6.0	Lentisk brush – f.a.z.	5.0	Hazel brush – p.a.z.	10.0
Lentisk brush – c.a.z.	5.8	Lentisk brush – c.a.z.	4.2	Lentisk brush – c.a.z.	10.0
L. bulrush brush – f.a.z.	5.5	Hazel brush – p.a.z.	3.7	Hazel brush – c.a.z.	9.4
Lentisk brush – f.a.z.	3.8	Lentisk brush – p.a.z.	3.4	Lentisk brush – f.a.z.	8.8
Hazel brush – f.a.z.	3.0	Hazel brush – c.a.z.	2.0	Lentisk brush – p.a.z.	5.2
Lentisk brush – p.a.z.	1.8	Hazel brush – f.a.z.	1.6	Hazel brush – f.a.z.	4.6

Table 4 Results of the efficiency analysis of plant fragments. Yellow: tools whose performance level was classified as Medium (EI: 5.0 – 7.9; ovr-EI: 10.0 – 15.9); Red: tools whose performance level was classified as Low (EI: 0 – 4.9; ovr-EI: 0.0 – 9.9)

Straight lines		Curved lines		Straight and curved lines	
Tool	EI	Tool	EI	Tool	Ovr EI
Kermes oak branch – p.a.z.	6.4	Rush branch – p.a.z.	6.5	Reed branch – p.a.z.	11.5
Reed branch – p.a.z.	5.5	Reed branch – p.a.z.	6.0	Rush branch – p.a.z.	10.4
Hazel branch – p.a.z.	4.4	Lentisk branch – p.a.z.	5.8	Kermes oak branch – p.a.z.	9.7
Rush branch – p.a.z.	3.9	L. bulrush branch – p.a.z.	4.8	Hazel branch – p.a.z.	8.4
Mallow root – p.a.z.	3.5	Hazel branch – p.a.z.	4.0	Lentisk branch – p.a.z.	8.2
L. bulrush branch – p.a.z.	2.5	Kermes oak branch – p.a.z.	3.3	L. bulrush branch – p.a.z.	7.3
Lentisk branch – p.a.z.	2.4	M. spurge branch – p.a.z.	3.2	Mallow root – p.a.z.	6.1
M. spurge branch – p.a.z.	1.6	Mallow root – p.a.z.	2.6	M. spurge branch – p.a.z.	4.8

Table 5 Results of the efficiency analysis of feathers. Green: tools whose performance level was classified as High (EI: 8.0 – 10.0; ovr-EI: 16.0 – 20.0); Yellow: tools whose performance level was classified as Medium (EI: 5.0 – 7.9; ovr-EI: 10.0 – 15.9); Red: tools whose performance level was classified as Low (EI: 0 – 4.9; ovr-EI: 0.0 – 9.9)

Straight lines		Curved lines		Straight and curved lines	
Tool	EI	Tool	EI	Tool	Ovr EI
Crow feather – p.a.z.	9.5	Rock dove feather – p.a.z.	5.5	Crow feather – p.a.z.	14.0
Rock dove feather – c.a.z.	6.6	Crow feather – p.a.z.	4.5	Rock dove feather – p.a.z.	10.6
S. sparrow feather – p.a.z.	6.3	S. sparrow feather – c.a.z.	4.2	S. sparrow feather – p.a.z.	10.3
Crow feather – c.a.z.	6.0	Crow feather – c.a.z.	4.1	S. sparrow feather – c.a.z.	10.2
S. sparrow feather – c.a.z.	6.0	S. sparrow feather – p.a.z.	4.0	Crow feather – c.a.z.	10.1
Rock dove feather – p.a.z.	5.1	Rock dove feather – c.a.z.	3.5	Rock dove feather – c.a.z.	10.1

Table 6 Results of the efficiency analysis of feather fragments. Yellow: tools whose performance level was classified as Medium (EI: 5.0 – 7.9; ovr-EI: 10.0 – 15.9); Red: tools whose performance level was classified as Low (EI: 0 – 4.9; ovr-EI: 0.0 – 9.9)

Straight lines		Curved lines		Straight and curved lines	
Tool	EI	Tool	EI	Tool	Ovr EI
P.p. rock dove feather – c.a.z.	6.3	L.p. rock dove feather – c.a.z.	4.5	P.p. rock dove feather – p.a.z.	8.5
P.p. rock dove feather – p.a.z.	5.5	P.p. rock dove feather – p.a.z.	3.0	L.p. rock dove feather – c.a.z.	8.0
L.p. rock dove feather – c.a.z.	3.5	L.p. rock dove feather – p.a.z.	2.0	P.p. rock dove feather – c.a.z.	8.0
L.p. rock dove feather – p.a.z.	2.0	P.p. rock dove feather – c.a.z.	1.7	L.p. rock dove feather – p.a.z.	4.0
Cal. rock dove feather – p.a.z.	1.8	Cal. rock dove feather – p.a.z.	1.6	Cal. rock dove feather – p.a.z.	3.4
Cal. rock dove feather – c.a.z.	0.4	Cal. rock dove feather – c.a.z.	1.0	Cal. rock dove feather – c.a.z.	1.4
Rac. rock dove feather – p.a.z.	0.0	Rac. rock dove feather – p.a.z.	0.0	Rac. rock dove feather – p.a.z.	0.0

with the intrinsic properties of their raw material. In this context, brushes made from fibrous, spongy and woody plants reached their peak performances when crafted with flat, pointed, and both pointed and convex bristles, respectively. The importance of this proper combination between raw material and active zone also becomes evident when comparing plant brushes with plant fragments with a whittled point. Out of the eight tools that comprise this latter category, two exhibited a medium PL (ovr-EI: 10.4 – 11.5), while the remaining six tools were rated with low PLs (ovr-EI: 4.8 – 9.7) (Table 4). Also, the highest ovr-EIs of the tools made from rush, lesser bulrush, hazel and lentisk were considerably lower than those presented by the brushes produced with these plants, suggesting that tools whose active zone is formed by bristles tend to be more efficient than those with a whittled end (Fig. 7f). It should also be noted

Table 7 Results of the efficiency analysis of feather brushes. Yellow: tools whose performance level was classified as Medium (EI: 5.0 – 7.9; ovr-EI: 10.0 – 15.9); Red: tools whose performance level was classified as Low (EI: 0 – 4.9; ovr-EI: 0.0 – 9.9)

Straight lines		Curved lines		Straight and curved lines	
Tool	**EI**	**Tool**	**EI**	**Tool**	**Ovr EI**
R. dove brush (pp) – p.a.z.	7.7	R. dove brush (pp) – p.a.z.	6.3	R. dove brush (pp) – p.a.z.	14.0
S. sparrow brush (r) – p.a.z.	7.7	S. sparrow brush (r) – p.a.z.	6.0	S. sparrow brush (r) – p.a.z.	13.7
S. sparrow brush – p.a.z.	6.6	R. dove brush (lp) – c.a.z.	5.7	S. sparrow brush – p.a.z.	10.5
R. dove brush (pp) – c.a.z.	5.8	R. dove brush (pp) – c.a.z.	4.1	R. dove brush (pp) – c.a.z.	9.9
R. dove brush (lp) – c.a.z.	3.9	S. sparrow brush – p.a.z.	3.9	R. dove brush (lp) – c.a.z.	9.6
R. dove brush (lp) – p.a.z.	3.2	R. dove brush (lp) – p.a.z.	2.1	R. dove brush (lp) – p.a.z.	5.3

Fig. 7 Example of the straight and curved lines produced with the different types of experimental paint application tools: a) bull hair brush – p.a.z; b) deer hair brush – c.a.z; c) rabbit hair brush – p.a.z; d) rush brush – c.a.z.; e) hazel brush – c.a.z.; f) rush fragment – p.a.z.; g) crow feather – p.a.z; h) rock dove feather fragment (lp) – p.a.z; i) rock dove feather brush (pp) – p.a.z

that, in this category of tools, no predominance of a specific type of raw material in terms of performance was observed, as fibrous (rush, mallow, and Mediterranean spurge), spongy (Lesser bulrush), and woody plants (hazel, lentisk, kermes oak, and dry reed) appear distributed throughout the entire classification table.

Concerning the feathers, all six tools exhibited a medium PL (ovr-EI: 10.1 –14.0) (Table 5). The best results were achieved through the use of a crow feather, apparently because its behaviour is more stable than that of smaller feathers during the execution of technical gestures (Fig. 7g). Even so, a significant reduction in performance was noted when this tool –as well as the other feathers– was employed to paint curved lines. Furthermore, it was observed that for the three types of feathers tested, the highest ovr-EIs were obtained using pointed tools, which highlights, once again, the importance of compatibility between the properties of the raw material and the morphology of the active zone.

On the other hand, the seven feather fragments exhibited a low PL (ovr-EI: 0.0 – 8.5) (Table 6). Besides indicating that hard parts of the feather, such as the calamus and rachis, are not suitable paint application tools, the data suggest that modifications in the feather structure tend to make their technical behaviour more unstable and unpredictable, resulting in a limited efficiency that manifests in tools with both pointed and convex active zones (Fig. 7h). However, this instability in the technical behaviour of the feather fragments can be minimized by hafting them to create feather brushes. Out of the six tools in this category, three exhibited a medium PL (ovr-EI: 10.5 – 14) (Table 7) and three a low PL (ovr-EI: 5.3 – 9.9). These data suggest that the hafting of both feather fragments and small feathers tends to substantially improve their efficiency by facilitating the prehension of the tool, thereby providing enhanced control and precision in executing technical gestures (Fig. 7i). In this category, tools with a pointed active zone outperformed those with convex bristles, as observed in the case of raw feathers. Additionally, it was observed that using pine resin to attach the Spanish sparrow feather to a reed haft increased the stability of the active zone and contributed to the tool exhibiting better performance.

Drawing on these experimental findings, it was possible to identify the most efficient paint application tools at both individual and category levels. At the individual level, the bull hair brush with a pointed active zone, the boar hair brush with a flat active zone, and the crow feather with a pointed active zone proved to be the most efficient tools for painting straight lines, each displaying an EI of 9.5. Concerning the production of curved lines, the bull hair brush with a pointed active zone stood alone at the top of the ranking, maintaining an EI of 9.5 while the other tools showed lower values. This remarkable performance when used to paint both types of experimental marks resulted in an ovr. EI of 19.0, making this bull hair brush the most efficient of all the tools tested.

At the tool category level, the results exhibited some variations. Based on their average performance, feathers were found to be the most suitable tools for painting straight lines, with an avg. EI of 6.58. They were closely followed by hair brushes (avg. EI of 6.48), and then by plant brushes (avg. EI of 5.88), feather brushes (avg. EI of 5.82), plant fragments (avg. EI of 3.78), and feather fragments (EI of 2.79). In the production of curved lines, hair brushes demonstrated superior efficiency, achieving an avg. EI of 5.25. They were followed by plant brushes and feather brushes (both with an avg. EI of 4.68), plant fragments (avg. EI of 4.53), feathers (avg. EI of 4.30), and feather fragments (avg. EI of 1.97) (Fig. 8).

As can be seen in Fig. 8, nearly all tool categories exhibited functional variability and a significant reduction in performance when used to paint curved lines. This is attributed to the fact that the bristles that form the active zone of several tools tended to splay –with varying degrees of extent– during the execution of curvilinear movements, which leads to a decrease in precision and adaptability to the support surface (Fig. 9). This phenomenon is especially notable in the case of feathers, due to the high fragility and flexibility of their barbs. Exception to this general trend are the plant fragments, whose active zone is not composed of bristles. In the case of these tools, the curvilinear technical gestures allow for a more efficient discharge of paint onto the wall, since the contact against the support involves a wider portion of the active zone. In addition, the more pronounced diagonal angle between the tool and the wall –essential for creating curved lines– tends to facilitate their adaptability to the support surface, which in most cases also contributes to an improvement in precision. Therefore, taking into account this functional variability exhibited by the experimental paint application tools, the most efficient for painting both straight and curved lines were, in this order, the hair brushes (ovr. EI: 11.73), the feathers (ovr. EI: 10.88), the plant brushes (ovr. EI: 10.56), the feather brushes (ovr. EI: 10.50), the plant fragments (ovr. EI: 8.31), and the feather fragments (ovr. EI: 4.76).

Determining the level of correlation between the morphology of the tool's active zone and the morphology of the line tips

The data summarized in Table 8 and detailed further in the Supplementary Material (Section "6"), enabled the determination of the level of correlation between the morphology of the tool's active zone and the morphology of the 1200 line tips. Thus, regarding the 30 paint application tools with a pointed active zone, the level of correlation was predominantly low (CI: 1 – 2) for both the initial (N = 13) and final tips (N = 14) of straight lines. In the curved lines, the correlation primarily ranged between medium (CI: 3 – 4) and non-existent (CI: 0) for the initial tips (both levels with N = 9), and remained predominantly low for the final tips (N = 13). In the case of the 19 tools with a convex active zone, the level of correlation was mainly medium for the

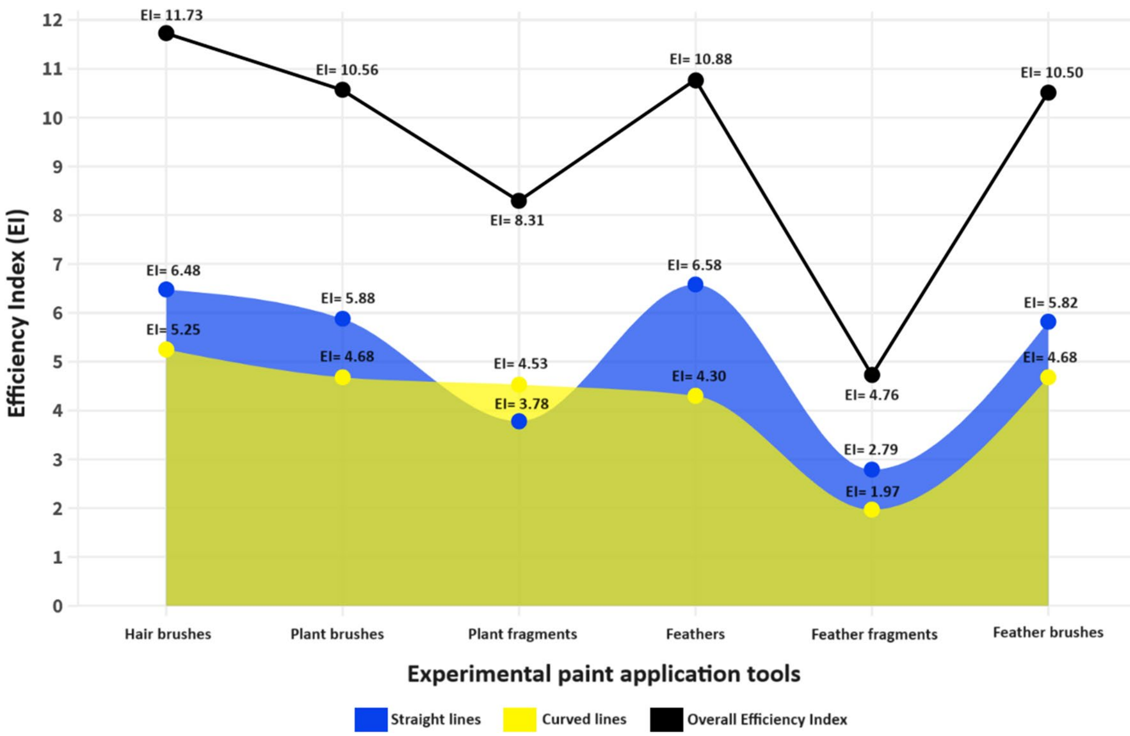

Fig. 8 Efficiency Index (EI) of the six categories of experimental paint application tools

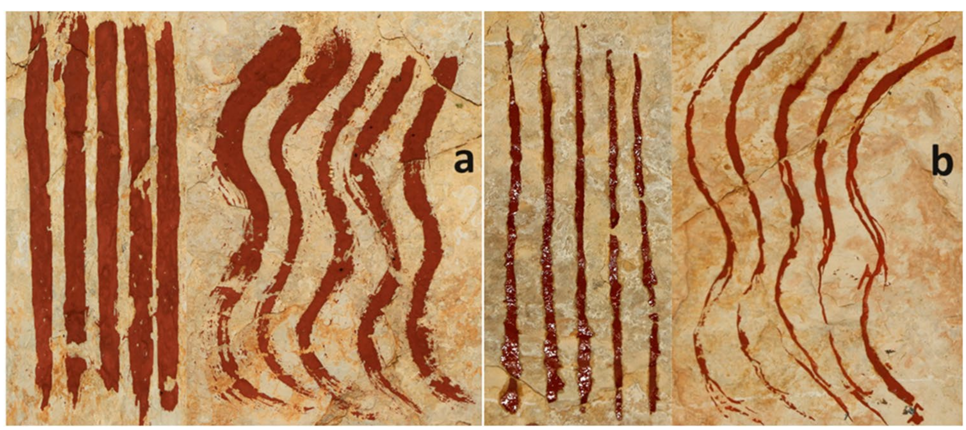

Fig. 9 Examples of precision and adaptability problems caused by the splaying of the tool's bristles during the production of curved lines: a) boar hair brush – c.a.z; b) rock dove feather – c.a.z

initial tips (N = 8) and non-existent for the final tips (N = 9) of straight lines. These levels of correlation were also predominant in curved lines, with a majority of cases classified as medium for the initial tips (N = 8) and non-existent for the final tips (N = 13). Finally, concerning the 11 tools with a flat active zone, the level of correlation in straight lines was predominantly between medium and low for the initial tips (both levels with N = 5), and mainly non-existent for the final tips (N = 5). In the case of curved lines, it was essentially non-existent in the initial tips (N = 6) and low in the final tips (N = 7).

These data demonstrate that the assumption that the morphology of the line tips tends to reflect the morphology of the tool's active zone lacks empirical support. In this sense, in straight lines produced with tools having a pointed active zone, only four cases of high correlation (CI: 5) were identified in the initial tips, while in curved lines, six cases were detected in the initial tips and one in the final tips. This implies that even when a high correlation was observed, it accounted for no more than 20% (maximum N = 6) of cases analysed. Furthermore, concerning the experimental marks painted with tools with a convex active zone, two

Table 8 Classification of the level of correlation between the morphology of the active zone and the morphology of the line tips in each tool category. H = High (CI: 5), M = Medium (CI: 3 – 4), L = Low (CI: 1 – 2), NE = Non-existent (CI: 0)

Experimental paint application tools	N	Straight lines								Curved lines							
		Initial tip				Final tip				Initial tip				Final tip			
		N of tools for each level of correlation				N of tools for each level of correlation				N of tools for each level of correlation				N of tools for each level of correlation			
		H	*M*	*L*	*NE*	*H*	*M*	*L*	*NE*	*H*	*M*	*L*	*NE*	*H*	*M*	*L*	*NE*
Hair brushes – p.a.z	7	2	0	2	3	0	0	4	3	1	2	4	0	0	2	3	2
Plant brushes – p.a.z	4	1	0	2	1	0	0	3	1	1	1	0	2	0	1	2	1
Plant fragments – p.a.z	8	0	0	3	5	0	0	2	6	0	2	1	5	0	5	2	1
Feathers – p.a.z	3	1	1	1	0	0	1	2	0	1	2	0	0	0	0	3	0
Feather fragments – p.a.z	4	0	1	2	1	0	0	2	2	1	2	0	1	1	1	1	1
Feather brushes – p.a.z	4	0	1	3	0	0	3	1	0	2	0	1	1	0	2	2	0
Total	30	4	3	13	10	0	4	14	12	6	9	6	9	1	11	13	5
Hair brushes – c.a.z	7	0	2	3	2	0	1	2	4	0	4	2	1	0	0	3	4
Plant brushes – c.a.z	4	1	2	1	0	0	1	1	2	0	2	2	0	0	0	1	3
Feathers – c.a.z	3	0	0	3	0	0	0	2	1	0	0	1	2	0	0	1	2
Feather fragments – c.a.z	3	1	2	0	0	0	0	1	2	1	2	0	0	0	0	0	3
Feather brushes – c.a.z	2	0	2	0	0	0	0	2	0	1	0	0	1	0	0	1	1
Total	19	2	8	7	2	0	2	8	9	2	8	5	4	0	0	6	13
Hair brushes – f.a.z	7	0	2	3	2	0	2	1	4	0	0	2	5	0	0	5	2
Plant brushes – f.a.z	4	0	2	1	1	0	0	3	1	0	1	2	1	0	2	2	0
Total	11	0	4	4	3	0	2	4	5	0	1	4	6	0	2	7	2

examples of high correlation were identified in the initial tips of straight lines and another two in the initial tips of curved lines, which in each case account for only 10.5% (maximum N = 2) of the sample. Among the lines painted using tools with a flat active zone, no instances of high correlation were identified.

It is worth noting that, in the case of pointed tools, the correlation is stronger in the curved lines when compared to the straight lines. For both the initial and final tips of the curvilinear marks, there is a higher number of cases where the level of correlation is high or medium and a lower number of cases classified as low or non-existent. This trend was reversed in the case of tools with convex bristles, where higher levels of correlation were observed in both the initial and final tips of straight lines. In the case of the tools with flat active zones, the initial tips showed higher levels of correlation in straight lines and the final tips in curved lines. Thus, with the exception of these instances in which tools with flat bristles were used to paint curves, high and medium correlation levels were more frequently observed in the initial tips of both straight and curved lines. This suggests that, compared to the final tips, the initial tips are more likely to yield diagnostic information regarding the active zone of the paint application tools.

Discussion: integrating experimental and archaeological data

Identifying the experimental paint application tools most similar to the Levantine ones

The comparison between the archaeological and the experimental samples enabled the determination of the degree of similarity between them and the identification of the paint application tools that produced straight and curved lines with features analogous to the prehistoric ones (Table 9). To provide a comprehensive visualization of the comparison results, the similarity indices assigned to the lines produced with each experimental tool were plotted in the graph presented in Fig. 10, in which they were also contrasted with the tool's efficiency indices.

Regarding the straight lines, 10 out of 60 tested tools (16,67%) were able to produce experimental marks with the highest degree of similarity (SI: 10) to the archaeological sample. Among these, hair brushes were the most prevalent (N = 5), followed by plant brushes (N = 3) and feather brushes (N = 2). Also, tools with a pointed active zone predominated over those with convex (N = 3) and flat bristles (N = 2). When it comes to curved lines, four tools (6,67%) were capable of producing paintings highly

Table 9 The paint experimental paint application tools that produce lines highly similar to those found in the nine rock art sites addressed in this study

Tool category	Straight lines highly similar to the archaeological sample	Curved lines highly similar to the archaeological sample
Hair brushes	Bull hair brush – p.a.z Human hair brush – p.a.z Deer hair brush – c.a.z Boar hair brush – f.a.z Human hair brush – f.a.z	Bull hair brush – p.a.z Human hair brush – p.a.z
Plant brushes	Lesser bulrush brush – p.a.z Hazel brush – c.a.z Rush brush – c.a.z	Lesser bulrush brush – p.a.z Rush brush – c.a.z
Feather brushes	Rock dove feather brush (pp) – p.a.z S. sparrow feather brush (r) – p.a.z	———

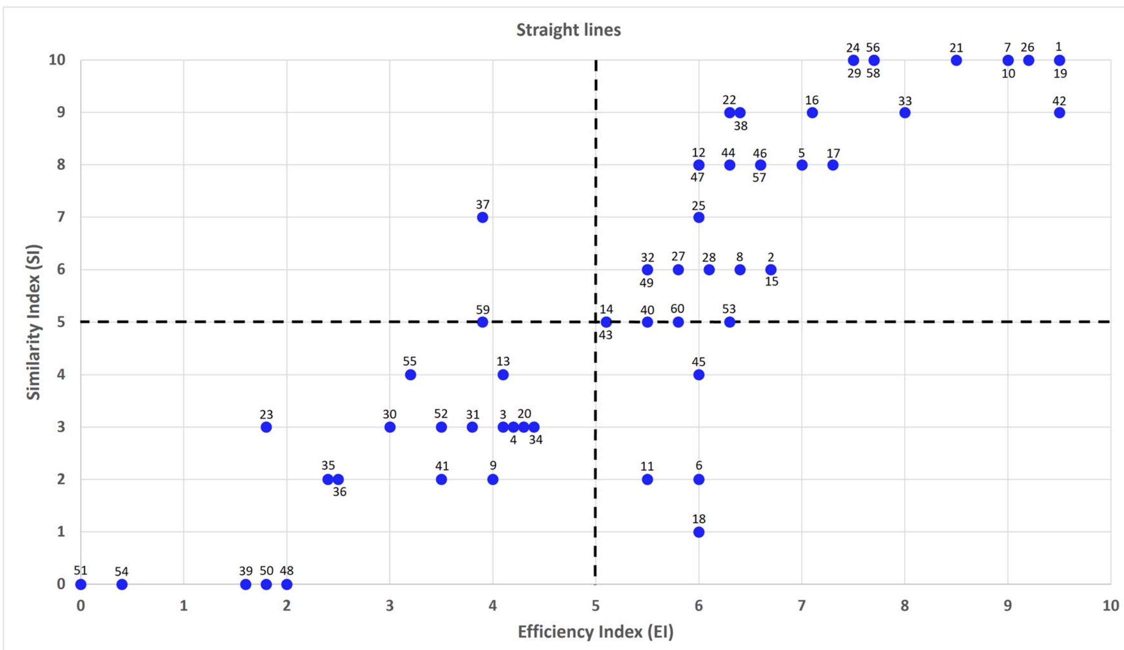

Fig. 10 Analysis of the relationship between the Efficiency Index (EI) of the experimental tools and the Similarity Index (SI) assigned to the straight lines produced with them: 1) bull hair brush – p.a.z.; 2) goat hair brush – p.a.z.; 3) deer hair brush – p.a.z.; 4) rabbit hair brush – p.a.z.; 5) boar hair brush – p.a.z.; 6) fox hair brush – p.a.z.; 7) human hair brush – p.a.z.; 8) bull hair brush – c.a.z.; 9) goat hair brush – c.a.z.; 10) deer hair brush – c.a.z.; 11) rabbit hair brush – c.a.z.; 12) boar hair brush – c.a.z.; 13) fox hair brush – c.a.z.; 14) human hair brush – c.a.z.; 15) bull hair brush – f.a.z.; 16) goat hair brush – f.a.z.; 17) deer hair brush – f.a.z.; 18) rabbit hair brush – f.a.z.; 19) boar hair brush – f.a.z.; 20) fox hair brush – f.a.z.; 21) human hair brush – f.a.z.; 22) hazel brush – p.a.z.; 23) lentisk brush – p.a.z.; 24) lesser bulrush brush – p.a.z.; 25) rush brush – p.a.z.; 26) hazel brush – c.a.z.; 27) lentisk brush – c.a.z.; 28) lesser bulrush brush – c.a.z.; 29) rush brush – c.a.z.; 30) hazel brush – f.a.z.; 31) lentisk brush – f.a.z.; 32) lesser bulrush brush – f.a.z.; 33) rush brush – f.a.z.; 34) hazel branch – p.a.z.; 35) lentisk branch – p.a.z.; 36) lesser bulrush branch – p.a.z.; 37) rush branch – p.a.z.; 38) kermes oak brush – p.a.z.; 39) Mediterranean spurge branch – p.a.z.; 40) reed branch – p.a.z.; 41) mallow root – p.a.z.; 42) crow feather – p.a.z.; 43) rock dove feather – p.a.z.; 44) Spanish sparrow feather – p.a.z.; 45) crow feather – c.a.z.; 46) rock dove feather – c.a.z.; 47) Spanish sparrow feather – c.a.z.; 48) lateral part of rock dove feather – p.a.z.; 49) proximal part of rock dove feather – p.a.z.; 50) calamus of rock feather – p.a.z.; 51) rachis of rock dove feather – p.a.z.; 52) lateral part of rock dove feather – c.a.z.; 53) proximal part of rock dove feather – c.a.z.; 54) calamus of rock feather – c.a.z.; 55) brush of rock dove feather (lateral part) – p.a.z.; 56) brush of rock dove feather (proximal part) – p.a.z.; 57; brush of Spanish sparrow feather – p.a.z.; 58) brush of Spanish sparrow feather fixed with resin – p.a.z.; 59) brush of rock dove feather (lateral part) – c.a.z.; 60) brush of rock dove feather (proximal part) – c.a.z

similar to the Levantine images. In this case, hair brushes (N = 2) and plant brushes (N = 2) with pointed (N = 3) and convex active zones (N = 1), which also rank among the 10 tools that produced highly similar straight lines. This implies that only four tools afforded the production of both straight and curved lines with techno-visual features equivalent to those of the Levantine paintings – two hair brushes and two plant brushes.

A closer examination of these results also allows us to investigate the relationship between tool efficiency and similarity to the archaeological sample (Fig. 10 and Fig. 11). In both straight and curved lines a considerable number of tools whose PL was classified as medium (EI: 5 – 7.9) rank among those that produced lines equivalent to the depictions found at the rock art sites. This observation is important insofar as it implies that the production of rock art motifs with technical characteristics analogous to the Levantine paintings does not necessarily require the use of tools with the highest level of efficiency, but rather the use of tools that can afford the creation of lines with a specific set of techno-visual features. However, unlike tools with a high PL (EI: 8–10), which consistently allow for the production of paintings that reflect their high precision, adaptability to the support surface, and paint load capacity, those with a medium PL exhibit more unstable and sometimes unpredictable technical behaviour. Consequently, their use requires greater amounts of time, energy, knowledge and technical skill, which together converge to result in a higher labour investment.

Another noteworthy point is that no tool with an EI lower than 6.0 ranks among those that produced lines highly similar to the study sample. This suggests that although tools with a medium PL could afford the production of Levantine motifs, they must possess a level of efficiency that is at least sufficient to enable the technical operation and the creation of images with the desired techno-visual features. This evidence demonstrates that, contrary to common assumptions, the mere fact that a tool allows the application of paint onto a wall does not make it automatically suitable for use as a tool for painting rock art. This entails that the production of

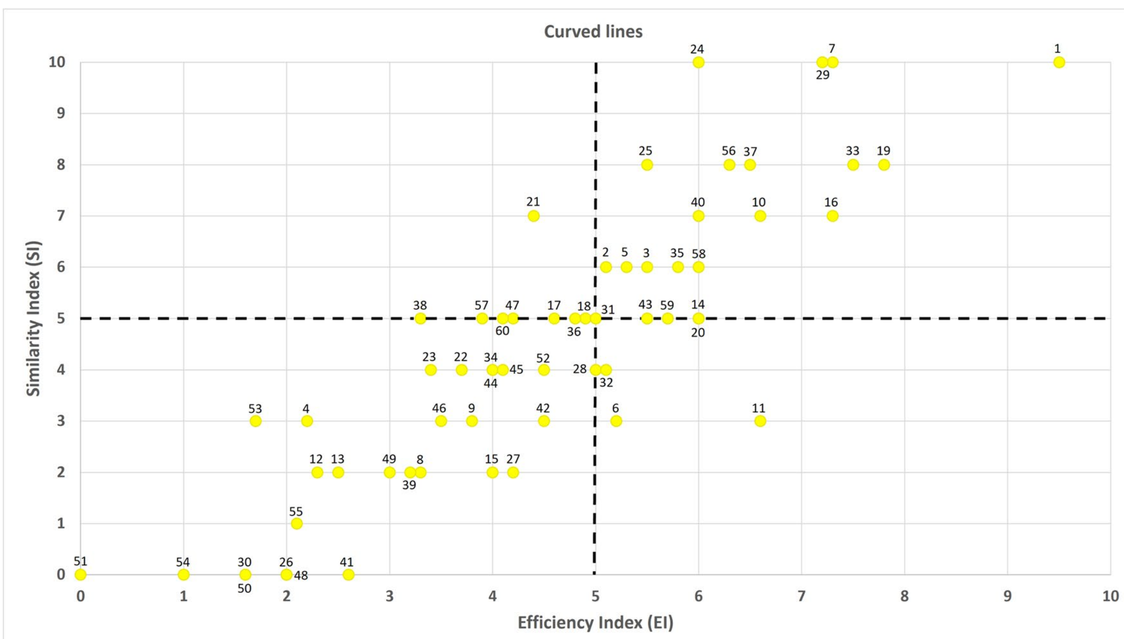

Fig. 11 Analysis of the relationship between the Efficiency Index (EI) of the experimental tools and the Similarity Index (SI) assigned to the curved lines produced with them: 1) bull hair brush – p.a.z.; 2) goat hair brush – p.a.z.; 3) deer hair brush – p.a.z.; 4) rabbit hair brush – p.a.z.; 5) boar hair brush – p.a.z.; 6) fox hair brush – p.a.z.; 7) human hair brush – p.a.z.; 8) bull hair brush – c.a.z.; 9) goat hair brush – c.a.z.; 10) deer hair brush – c.a.z.; 11) rabbit hair brush – c.a.z.; 12) boar hair brush – c.a.z.; 13) fox hair brush – c.a.z.; 14) human hair brush – c.a.z.; 15) bull hair brush – f.a.z.; 16) goat hair brush – f.a.z.; 17) deer hair brush – f.a.z.; 18) rabbit hair brush – f.a.z.; 19) boar hair brush – f.a.z.; 20) fox hair brush – f.a.z.; 21) human hair brush – f.a.z.; 22) hazel brush – p.a.z.; 23) lentisk brush – p.a.z.; 24) lesser bulrush brush – p.a.z.; 25) rush brush – p.a.z.; 26) hazel brush – c.a.z.; 27) lentisk brush – c.a.z.; 28) lesser bulrush brush – c.a.z.; 29) rush brush – c.a.z.; 30) hazel brush – f.a.z.; 31) lentisk brush – f.a.z.; 32) lesser bulrush brush – f.a.z.; 33) rush brush – f.a.z.; 34) hazel branch – p.a.z.; 35) lentisk branch – p.a.z.; 36) lesser bulrush branch – p.a.z.; 37) rush branch – p.a.z.; 38) kermes oak brush – p.a.z.; 39) Mediterranean spurge branch – p.a.z.; 40) reed branch – p.a.z.; 41) mallow root – p.a.z.; 42) crow feather – p.a.z.; 43) rock dove feather – p.a.z.; 44) Spanish sparrow feather – p.a.z.; 45) crow feather – c.a.z.; 46) rock dove feather – c.a.z.; 47) Spanish sparrow feather – c.a.z.; 48) lateral part of rock dove feather – p.a.z.; 49) proximal part of rock dove feather – p.a.z.; 50) calamus of rock feather – p.a.z.; 51) rachis of rock dove feather – p.a.z.; 52) lateral part of rock dove feather – c.a.z.; 53) proximal part of rock dove feather – c.a.z.; 54) calamus of rock feather – c.a.z.; 55) brush of rock dove feather (lateral part) – p.a.z.; 56) brush of rock dove feather (proximal part) – p.a.z.; 57; brush of Spanish sparrow feather – p.a.z.; 58) brush of Spanish sparrow feather fixed with resin – p.a.z.; 59) brush of rock dove feather (lateral part) – c.a.z.; 60) brush of rock dove feather (proximal part) – c.a.z

LRA is a technically complex process that required the use of tools with specific characteristics, which is corroborated by the observation that only lines produced with artefacts crafted as brushes achieved the highest level of similarity with the archaeological images.

These results provide empirical support for the proposals according to which LRA was produced through the use of hair brushes, plant brushes, and feather brushes (see Table 1). In particular, the data endorse Bea's (2007) first impressions concerning the employment of these categories of tools and are also consistent with the observations made by Ruiz (2012) regarding the potential use of hair brushes. However, the assumptions regarding the identification of lines painted with feathers, based solely on the convex morphology of the initial tips and the pointed form of the final tips (Ruiz 2012), should be approached with great caution. As observed in our analysis of the correlation between the tool's active zone and the morphology of the line tips it produces, out of 30 initial tips and 30 final tips experimentally produced with pointed feathers, only six initial tips exhibited a convex morphology and 12 final tips presented a pointed shape (see Supplementary Material – Section "6" – Tables 85 and 98). In the remaining cases, the tips showed different forms, and in only two of the 30 lines analysed did a convex initial tip appear associated with a pointed final tip. Furthermore, this analysis revealed that all tool categories and all types of active zones tested are capable of producing lines with convex initial tips and pointed final tips, suggesting that, in most instances, the shape of the tips is more influenced by the mechanics of the technical gesture and the amount of paint in the active zone than by the morphology of the latter. This implies that lines whose tips exhibit the characteristics previously mentioned as indicative of the use of feathers could have been produced through the use of other tools, such as hair or plant brushes.

Moreover, the experimental evidence refutes the widely disseminated proposal according to which feathers were the only paint application tool used in the production of Levantine images (Grimal and Alonso 2001). In this regard, the results demonstrate that lines highly similar to those found in LRA can be produced with other types of tools and that, actually, lines painted with raw feathers do not even rank among the most similar to the archaeological sample. Also, our data and practical experience challenge the idea that the crafting of brushes is a laborious and time-consuming process that would be beyond the technical capabilities of Levantine groups (Grimal and Alonso 2001). The experimental production of 39 brushes using hairs, plants, and feathers allowed us to establish that this is a technically simple procedure which, after the necessary raw materials for tool production have already been gathered, requires less than five minutes.

Unveiling the Levantine painters' toolkit

The insights derived from the integration of experimental and archaeological data enable us to draw a series of empirically-based inferences regarding the toolkit used by Levantine painters. Considering that the tools that produced experimental marks most similar to LRA (see Table 9) exhibit the highest probabilities of having been used to create the archaeological images, we can suggest that this toolkit likely consisted of hair brushes with pointed, convex, and flat active zones, plant brushes with pointed and convex active zones, and feather brushes with pointed active zones. Thus, for the production of hair brushes, prehistoric painters could have used hairs from humans and large animals such as bulls, boars, and deer, which are also widely represented in LRA and the archaeological contexts associated with the decorated shelters. To craft the plant brushes, they could have employed fibrous, spongy, and woody plants such as lesser bulrush, rush, and hazel, which are typical of the Levantine region and, in the case of the first two, are readily found in wet areas and around water courses close to the rock art sites. As for the feather brushes, they could have been made by hafting flight feathers from small birds, such as the Spanish sparrow, or fragments of feathers from medium-sized birds, like the rock dove, both of which are native species to the study area.

The number of tools comprising this toolkit would depend on its level of specialization. If the Levantine painters had opted for a generalist toolkit, they might have prioritized the use of brushes that exhibit high performance in producing both straight and curved lines, such as a bull hair brush with a pointed active zone or a rush brush with a convex active zone. On the other hand, if they opted for a more specialized toolkit, it might have included a greater number of tools with specific functions, such as brushes that are highly efficient at painting straight lines but less suitable for painting curves, such as a human hair brush with a flat active zone or a Spanish sparrow feather brush with a pointed active zone. However, the production of the 10 full-size replicas of rock art motifs allowed us to observe that to create images with the techno-visual features of LRA, even a generalist toolkit would need to include at least some specialized tools. In this sense, we found that brushes with a fine pointed active zone are necessary to accurately depict the millimetric anatomical features of human figures or the antlers and hooves of deer images, while it is more convenient to use brushes with convex or flat bristles and a larger diameter for painting the inner part of the motifs. Also, we noted that hair and plant brushes are more versatile because they can be crafted with different diameters, whereas feather brushes are limited by the reduced thickness of this raw material. This limitation implies that feather brushes are more suitable for painting the outlines and small details of the figures, whereas hair and plant brushes can perform the same task and also be used for filling the images.

The production of motif replicas also allowed us to explore the dynamics of the wear processes undergone by the paint application tools. In this regard, we observed that while plant brushes tend to show considerable wear due to the friction against the support surface (see Supplementary Material – Sect. “11”), hair and feather brushes did not exhibit any significant damage in their active zones. This suggests that plant brushes would likely have been considered expedient tools, as they not only wear out quickly but also have a limited capacity for maintenance and recycling –plant brushes tend to dry out within a few days, rendering them unusable. Conversely, hair brushes could be maintained for much longer and be easily recycled by replacing the worn bristles with new hair or feathers. Thus, we propose that hair and feather brushes fit into the category of curated technologies (Binford 1979: 261–266), and that they might have been used by the Levantine painters as personal gear –tools that would be crafted, maintained, transported, and recycled in anticipation of future painting activities. In contrast, plant brushes fit into the category of expedient technologies (ibid.) and might have been employed as situational gear –tools crafted to accomplish a specific task and in response to an immediate painting activity. Therefore, while the hair and feather brushes are likely to have been produced and curated to be reused, the plant brushes are likely to have been discarded after use and replaced by new tools, crafted from fresh plants just before painting the images.

As previously mentioned, scholars assert that the LRA from the nine sites constituting the study sample is the result of a common tradition, socially transmitted across generations (Obermaier 1938; Porcar 1945; Viñas 1982; Domingo Sanz 2012). Accordingly, it is pertinent to assume that the Levantine people passed down not only their graphic codes and knowledge about the production of the rock art motifs, but also the *chaîne opératoire* through which they crafted their tools, building true communities of practice and establishing an inextricable link between art production and knowledge transmission (Conkey 2009). Through this process, the brushes that comprised the Levantine toolkit transitioned from being mere artefacts used to apply paint to the walls of shelters to becoming the medium through which those prehistoric painters materialized their culture and identities into images.

Conclusion

After more than a century of controversies, the experimental approach developed in this study allowed us to test the validity of the hypotheses concerning the use of six different categories of paint application tools to produce LRA. The results show that out of 60 tools systematically tested through the production of 600 experimental marks, only 10 produced straight lines, four produced curved lines, and four produced both straight and curved lines, with techno-visual features equivalent to those of the archaeological paintings. This limited set of artifacts consists of hair brushes (N = 5), plant brushes (N = 3), and feather brushes (N = 2), which, configured with active zone morphologies suited to the intrinsic properties of the raw materials forming their bristles, could have composed the toolkit used by the Levantine painters. Employing these tools to produce 10 full-size replicas of Levantine motifs provided us with a better understanding of their potential role within the mentioned toolkit and allowed us to observe that hair and feather brushes could be curated and used as personal gear, while plant brushes would be employed as expedient situational gear. In this context, it is worth noting that five of the 10 tools that produced experimental marks highly similar to LRA exhibit a performance level classified as medium, which implies that, in certain cases, prehistoric painters might have opted for tools whose use required a greater labour investment but simultaneously offered high techno-visual affordances. Based on these data, we can suggest that LRA technology was not strictly based on an economic logic aimed at minimizing the costs associated with producing the images, but rather on a perspective where the priority was creating paintings with specific techno-visual qualities that reinforced the information transmitted through the graphic code.

The results also made it possible to refute the widespread hypothesis that feathers were the only paint application tool used in the production of LRA, as well as to demonstrate that crafting brushes with the resources available to prehistoric populations is a technically simple operation that requires low levels of labour investment. Additionally, the analysis of the experimental evidence revealed that the assumption according to which the morphology of line tips tends to reflect the morphology of the tool’s active zone lacks empirical support, and that the shape of such tips is highly influenced by the mechanics of the technical gestures executed during their creation. Therefore, these data provide a much deeper understanding of the technical and economic aspects that permeated LRA technology, a topic that has long been marginalized in the scholarly debates surrounding this prehistoric tradition.

Furthermore, these findings underscore the value of experimental archaeology as a rigorous method for testing the validity of our hypotheses about the past. In this sense, although the scope of the results generated by this investigation is focused on the post-Palaeolithic context of the LRA, extrapolation to similar cases is possible if undertaken with appropriate methodological caution. Moreover, the experimental protocol presented here can be widely adapted and employed as an analytical tool for systematically studying the production of prehistoric paintings from diverse chronologies and locations around the world. As the protocol is adopted by other scholars, it can be expanded by adding new variables, refined by creating new ways of measuring them, and applied to new contexts and research questions. We envision that this process will culminate in the collective construction of a robust approach to explore not only the technical and economic dimensions of rock art production but also the social and symbolic aspects that permeate the creation of these meaningful images.

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Author contribution Conceptualization: Neemias Santos da Rosa Methodology: Neemias Santos da Rosa, Danae Fiore, Ramon Viñas Formal analysis and investigation: Neemias Santos da Rosa, Ramon Viñas Writing—original draft preparation: Neemias Santos da Rosa Writing—review and editing: Neemias Santos da Rosa, Danae Fiore.

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Data availability Data used in this study are available to the public at the following repository: http://hdl.handle.net/10803/668379.

Declarations

Competing interests The authors declare no competing interests.

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