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ORIGINAL ARTICLE

Testing recipes: an experimental approach to paint production processes in Levantine rock art (Spain)

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Abstract

Over more than a century, several proposals have been made on the composition and technical features of the pictorial recipes used by Levantine prehistoric painters. In this paper all these proposals are surveyed and tested through systematic experiments to determine the technical affordance of pigments and binders in different pictorial recipes. Experimental results were then used as independent analytical parameters employed as diagnostic criteria to systematically study an archaeological sample of nine sites located in the Maestrazgo region (Spain) and their surroundings. Results reveal that out of 112 experimental recipes, only 16 afforded the production of paintings technically similar to Levantine rock art.

KEYWORDS

binders, experimental archaeology, Iberian Peninsula, Mesolithic, Neolithic, paint production, pigments, rock art, Spain

INTRODUCTION

Levantine rock art (LRA) is a singular cultural manifestation of European prehistory. Identified in more than a thousand open-air shelters throughout eastern Spain, this rock art was predominantly made using painting techniques, with very few cases of engraved or engraved/painted images. Levantine themes comprise hunting scenes, food gatherings, dances, and war conflicts (Domingo, 2005; Rubio et al., 2019; Santos Da Rosa et al., 2021). These images feature realistic-stylised human figures and naturalistic animal representations (mainly deer, goats, bulls, and boars), produced through thin lines and different surface treatments, among which solid-infilled in red are the most frequent. Debates regarding the chrono-cultural affiliation of this post-Palaeolithic rock art tradition have been constant in the history of research; currently, the main point of disagreement revolves around whether its origin dates back to the Epipaleolithic/Mesolithic or to the Neolithic (Arranz et al., 2012).

Since the LRA discovery in the early 20th century, several proposals have been made on the composition and characteristics of the pictorial recipes used by prehistoric painters (Santos da Rosa, 2019b).

However, such proposals are largely based on theoretical assumptions and inductive inferences that have not been rigorously tested, and due to the scarcity of systematic research on the subject, many aspects of the paint production processes remain unknown (Domingo et al., 2020). In order to obtain analytical parameters with independent validation that can be used as diagnostic criteria to study the archaeological images, we have surveyed all these proposals and considered them as hypotheses. These have been tested through a series of systematic experiments carried out with the following aims: (a) to assess the technical affordance of pigments and binders and their performance in different types of pictorial recipes; (b) to determine the most efficient paint recipes with high techno-visual affordances to produce experimental rock art marks similar to the LRA. We present the results of this experimental research and a series of empirically supported inferences about the painting production processes that underlie the creation of the Levantine paintings.

BACKGROUND KNOWLEDGE ON LEVANTINE PAINTINGS

To produce their rock art, Levantine painters used red, black, and white pigments with a wide range of shades. Red images are prevalent throughout the territory covered by this rock art tradition; black figures are less frequent but also not restricted to any geographical area; white colour has been identified only in certain regions of the territory, both in monochrome images and forming a few bichromies (Domingo et al., 2020; Lopez-Montalvo et al., 2014).

Different authors have proposed that the LRA paint recipes used by prehistoric artists were manufactured using iron oxides, manganese oxide, coal, charcoal, and kaolin, which were then mixed with binders such as water, saliva, blood, animal fat, egg white, honey, resins, and plant fluids (Alonso & Grimal, 1989, p. 18; Alonso & Grimal, 1999, p. 30–1; Bea, 2006–2007, p. 7; Beltrán, 1968, p. 27; Hernández-Pacheco, 1918, p. 67; Obermaier & Breuil, 1927, p. 514; Obermaier & Wernert, 1919, p. 15; Porcar et al., 1935; Ripoll, 1990, p. 72; Utrilla, 2000, p. 36; Viñas, 1982, p. 98; see Tables 1 and 2 in Supplementary Material). However, these proposals resulted from cursory observations of the paintings and from few and nonsystematic experiments.

From the 1990s, physicochemical analyses were carried out to accurately identify the composition of the pictorial recipes. These analyses identified the use of iron oxides— predominantly hematite— (Aramendia et al., 2020; Hernanz et al., 2006, 2010, 2014; Mas et al., 2013; Roldán et al., 2007, 2010, 2013) and a ferruginous aluminium silicate (Montes & Cabrera, 1992) for the production of red paintings. Likewise, they indicated the presence of manganese oxide (Pitarch et al., 2014; Roldán et al., 2007, 2010) and charcoal (Ballester et al., 2010; Lopez-Montalvo et al., 2014; López-Montalvo et al., 2017; Roldán et al., 2013) in black images, and the use of barium sulphate (Baldellou & Alloza, 2012) and a mixture of quartz-α, anatase, and illite (Hernanz et al., 2010) to obtain the white colour (see Table 3 in Supplementary Material).

In recent years, significant contributions have been made regarding the potential binders used in paint preparation. Analysing the black figures of Les Dogues shelter (Ares del Maestre, Castellón), López-Montalvo et al. (2017) found that the rock art motifs had been made with a charred plant matter pigment, composed of charcoal from the burning of angiosperms and conifers. According to the authors, the low definition of the images obtained by Scanning Electron Microscopy (SEM) entails that the charcoal powder was mixed with one or more binders of a fatty nature, which penetrated and filled in the plant cells, partially hiding their anatomical structure. By comparing with experimental black paint samples images, these researchers infer that the binders could have been animal fat or honey mixed with water or milk. In turn, Roldán et al. (2018), carried out a proteomic analysis on samples of red paintings from Coves de la Saltadora shelter (Coves de Vinromà, Castellón). They identified the presence of casein peptides of animal origin, which the authors consider as compatible with the use of milk as a binder in red paint production.

Nevertheless, despite the progress made in recent decades, there is still a considerable lack of information regarding the affordances that pigments and binders can provide to a pictorial recipe and their specific performance when combined to prepare paint. In particular, there is no systematic knowledge on the ease of applicability, the coverage capacity, and the adhesiveness that each of these components may provide when included in a paint mixture. To this end, we have developed the following experimental protocol to assess the affordances of each of these materials and their technical performances within different recipes.

TACKLING ROCK ART FROM ITS MATERIALITY: CONCEPTS AND METHODS

Rock art as a material culture product

The theoretical framework on which we base our research advocates the notion that rock art studies should not be constrained to stylistic classifications or symbolic interpretations, because these do not fully cover its actual complexity as a material culture product. Two key aspects of rock art's materiality are the technical processes and economic factors involved in its production.

The technical processes of rock art creation involve the types of raw materials, tools, technical gestures, and knowledge used along the production sequence to create visual images displayed on a bedrock (Fiore, 2018). In this paper, our analysis of these processes will focus on the assessment of the performance of different types of raw materials to produce paint recipes and of the techno-visual affordance of each of these recipes to produce highly similar features to those found on LRA images. Techno-visual affordances refer to visual features (e.g., shapes, sizes, colours, textures, etc.) that stem directly from the image-making techniques (e.g., single-stroke brush painting) and materials (e.g., paint recipe), which can afford particular ways of creation and expression by the artists (Fiore, 2020).

In turn, the economic factors of rock art production are the ways in which the work process has been organised along the production sequence, including workforces, labour division, and labour investment (Fiore, 2018). In this paper, we will refer to the yield of pigments and recipes according to the labour investment they require during their preparation and use.

From context to database: Shaping the sample

The first step of our research was to review more than 700 academic papers related to LRA, published between 1908 and 2021. Through this process, we compiled the main assumptions, proposals, data, and inferences concerning the technological processes of paint production and the components of pictorial recipes used by prehistoric artists. Next, we designed an experimental protocol in order to study the affordances and performances of pigments, binders, and recipes (presented in the next section). We then selected a study sample to serve as the basis for studying archaeological images via the experimental parameters. Many authors have argued that the LRA identified in the Maestrazgo region and surroundings is the result of a common tradition, culturally transmitted through generations (Domingo, 2012), in which "schools" might have operated in order to teach and maintain technical norms underlying the production process (Porcar, 1945, p. 32). As such, we decided to use this region as a reference model and analysed all photographic and technical documentation from two research projects led by R. Viñas that studied 19 sites in the area. Out of this database, nine sites were selected as key examples for the study of the paint production processes: Cova Remígia and Cingle de la Mola Remígia (Ares del Maestre, Castellón), Cova dels Cavalls, Cova del Civil and Abric del Mas d'en Josep (Tírig, Castellón), Cova Centelles (Albocàsser, Castellón), Cova dels Rossegadors (La Pobla de Benifassar, Castellón), Coves de la Saltadora (Coves de Vinromà, Castellón), and Abric d'Ermites I (Ulldecona, Tarragona) (1) (Figure 1).

The selection of the rock art sites was based on the following criteria: (a) the nine shelters are among the most studied since the discovery of the LRA, and there is a broad range of data related to them; (b) from technical, typological, and thematic points of view, the almost 3,000 figures identified

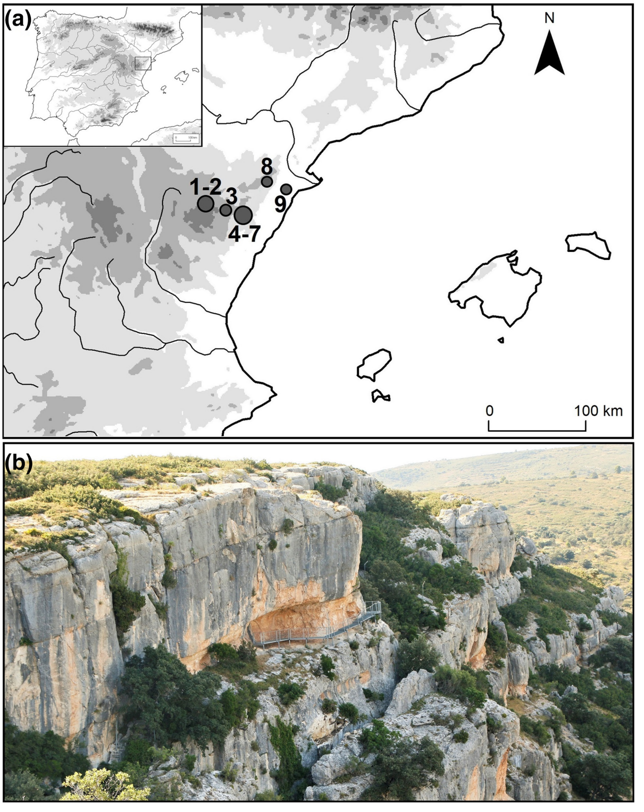

FIGURE 1 (a) Map of the study area with the location of the sites taken as archaeological references; (b) typical location of the Levantine shelters in the landscape (Cova dels Cavalls).

in these sites form a representative sample of the LRA found in the Maestrazgo region in particular and of this rock tradition in general (Figure 2); (c) in four of the selected sites (Cova Remígia, Cingle de la Mola Remígia, Cova dels Rossegadors, and Coves de la Saltadora) archaeometric studies were carried out (Hernanz et al., 2014; Lopez-Montalvo et al., 2014; Roldán et al., 2007, 2013, 2018) generating data on the paint pigments and potential binders, which are directly relevant for the comparisons with our experimental results.

The experimental protocol

In order to test the inductive inferences identified in the bibliographic review, we designed an experimental protocol that includes six steps: (a) gathering raw materials (pigments and binders) available in the region and verifying their composition through archaeometric techniques; (b) processing the materials under controlled conditions to produce paint; (c) using the paint in a systematic production of nonreplicative marks; (d) monitoring, recording, and analysing the experimental results through measurement of specific variables; (e) inferring analytical parameters from the experimental results, and (f) applying the experimental parameters as diagnostic criteria to analyse the LRA samples.

Five pigments were used: iron oxide (hematite, Fe_2O_3), manganese oxide (pyrolusite, MnO_2), charcoal, coal, and barium sulphate (barite, $BaSO_4$); and boar blood was also tested as a colouring substance. The mineral raw materials were obtained in deposits located in the study area and surroundings (Figure 3a). Ferruginous aluminium silicate, kaolin, and the mixture of quartz-α, anatase, and illite could not be tested due to the fact that we were unable to find natural deposits of these materials; using industrialised versions of them might have generated distorted results. The materials were

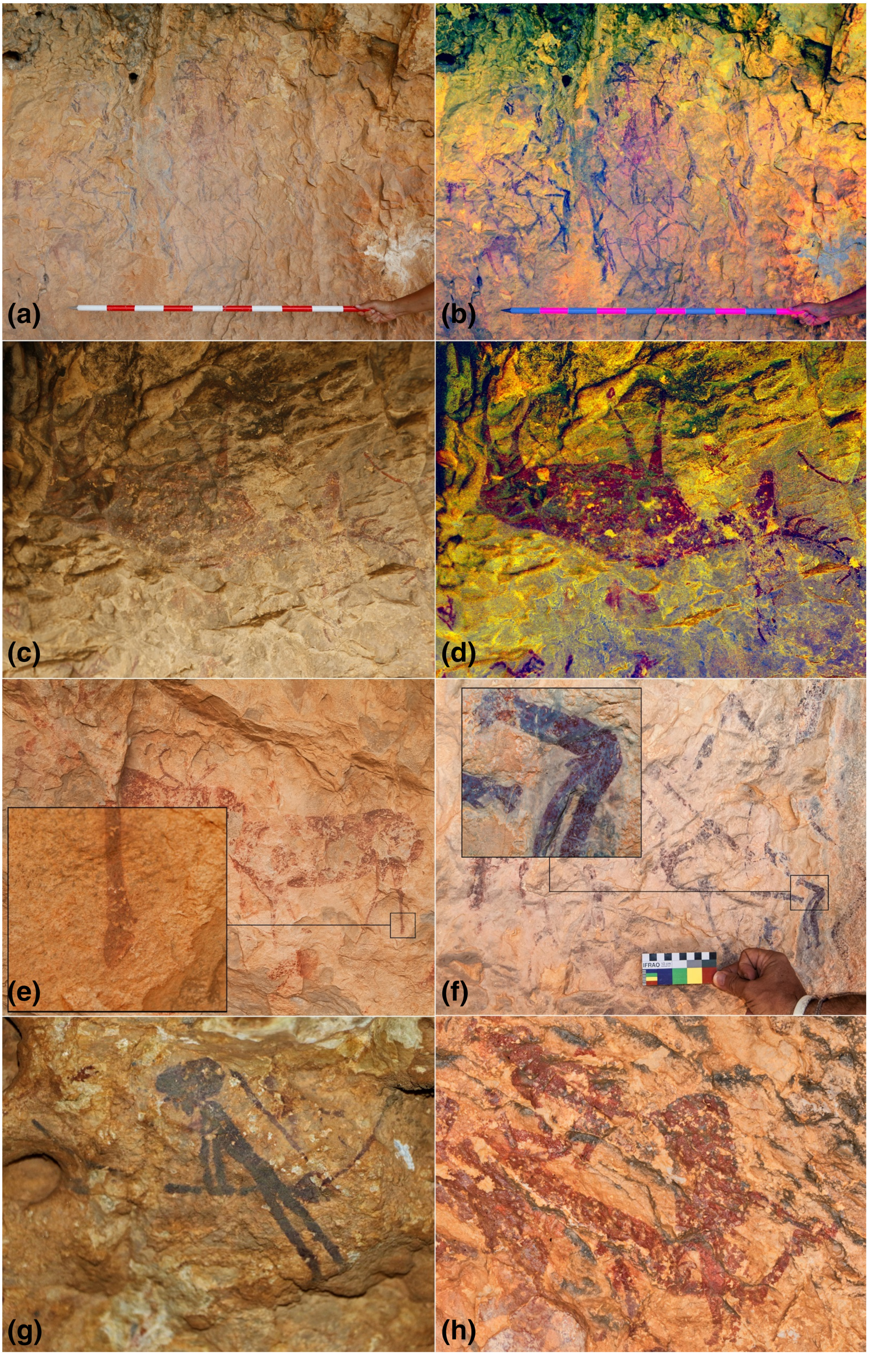

FIGURE 2 Examples of the techno-morphological features of LRA in the study area. (a-b) Central panel of Cova del Civil; (c-d) large red deer from Cova Remígia; (e) red deer with remarkable anatomical details from Cova dels Rossegadors (photo: A. Rubio); (d) anatomical features of a blackish archer from Cova del Civil (photo: A. Rubio); (e) black archer from Abric d'Ermites I; (f) red female figure with small white dots over the body painted in Cova Centelles (photo: A. Rubio).

FIGURE 3 Steps of the experimental protocol. (a) Gathering of mineral raw materials; (b) archaeometric analysis of pigments (X-ray diffraction performed on a fragment of hematite); (c) burning wood to obtain charcoal; (d) gathering of Mediterranean spurges to extract the latex used as a binder; (e-f) grinding of hematite to produce pigment powder; (g-h) preparation of experimental recipes by mixing pigments and binders; (i) production of experimental marks; (j) technical analysis of experimental images.

taken to the laboratory of Technical and Scientific Resources at Rovira i Virgili University, where the mineral pigments were submitted to X-Ray Diffraction (XRD) to verify their composition characteristics (Figure 3b). XRD measurements were made using a Bruker-AXS D8-Discover diffractometer equipped with a parallel incident beam (Göbel mirror), vertical θ-θ goniometer, XYZ motorised stage, and a GADDS (General Area Diffraction System).

To obtain charcoal, wood samples of angiosperms and gymnosperms (among them, conifers) that were available in the region in the early Holocene were gathered and burnt in controlled conditions: strawberry tree (*Arbutus unedo*), prickly juniper (*Juniperus oxycedrus*), Aleppo pine (*Pinus halepensis*), lentisk (*Pistacia lentiscus*), terebinth (*Pistacia terebinthus*), oak (*Quercus robur*), holm oak (*Quercus ilex*), and black hawthorn (*Rhamnus lycioides*) (Figure 3c). It is worth mentioning that charred wood remains of *Pinus* sp., *Quercus* sp., and *Juniperus* sp., as well as a fragment of *P. lentiscus* seed, were recovered during the excavation of the Mesolithic and Neolithic levels of Cova Fosca (Ares del Maestre, Castellón; Antolín et al., 2010), an archaeological site located in the centre of the study area, just 1 km away from Cova Remígia and Cingle de la Mola Remígia.

Based on the archaeological and paleoenvironmental evidence of the Maestrazgo region we used the following materials for binders: (1) water; (2) human saliva; (3) goat milk (*Capra hircus*); (4) boar blood (*Sus scrofa*); (5) boar fat (*S. scrofa*); (6) egg white (*Coturnix coturnix*); (7) egg yolk (*C. coturnix*); (8) egg (white + yolk; *C. coturnix*); (9) honey from bees (*Apis meliffera*); (10) latex from Mediterranean spurges (*Euphorbia characias*), and 11) resin from Aleppo pines (*P. halepensis*). The resin was collected directly from pine trunks, which naturally expel this substance through small crack points in their bark. Latex was obtained by cutting the stem and leaves of Mediterranean spurges (Figure 3d). The remaining binders were obtained via collaboration with herders, hunters, and beekeepers who work in the study area. Archaeological bone remains of *C. hircus*, *S. scrofa,* and *C. coturnix* were recovered during the aforementioned excavations at Cova Fosca (Olària, 1988).

The pigments used to manufacture the experimental paints were ground with quartzite and sandstone hammers on limestone platforms (Figure 3e and f). This process was carried out to produce a homogeneous powder with a particle size between 20 μm and 100 μm, equivalent to that identified in samples of Levantine paintings (Hernanz et al., 2012, p. 363). To test each colouring material's performance as a chromophore and ascertain whether they could be used to paint without any binder, six experimental recipes consisting only of 1 g/1 ml of pigment were prepared. Then, each of the five pigments was combined with each of the 11 binders in order to test their performances: during this procedure, each pigment was kept as a constant—the same amount of pigment from the same source was used in each experiment—and the tested variable was the binder. Thus, a total of 112 experimental pictorial recipes were prepared following this method (see Supplementary Material–Detailed experimental results, Tables 4–9).

Two sets of experimental paint recipes were made. The first set consisted of 51 simple-structure recipes (1 pigment + 1 binder) in which 1 g of each pigment was mixed with 1 g/1 ml of each binder (Figure 3g and h). Through this combination, it was possible to identify the binders' technical affordances and to compare their potentially different performances when interacting with each pigment. The second set consisted of 55 complex-structure recipes (1 pigment + 2 or more binders), which were produced to investigate the mixing potential of the combined binders and the feasibility of using paint recipes made by several components (see Supplementary Material–Synthesis of the experimental protocol). The quantity of pigment remained constant, whereas the variation depended on the binders' amount and proportion.

To test the efficiency of the pictorial recipes, five straight lines and five solid-infilled square figures were painted with each recipe. These experimental marks did not aim to replicate any Levantine motifs but aimed instead to produce highly comparable images that (a) make it easier to assess each recipe's efficiency; (b) make it possible to apply the resulting experimental parameters to the archaeological rock art record, because lines and solid-infilled figures are indeed two fundamental elements that constitute LRA motifs. Each experimental recipe was used to paint five solid-infilled squares ($4cm^2$) and five straight lines (4 cm long) with a rushes (*Juncus*) brush with a flat active zone on vertically positioned limestone slabs with similar morphology and texture to those of the limestone Levantine shelters (Figure 3i). The shape and number of experimental marks, the painting tool, and the rock slabs were kept constant throughout the experiment. To this end, one single brush was used throughout the process to avoid any possible variation due to a brush change. Thus, after testing each of the recipes, the brush was washed with water until all paint residues were removed.

Repeating the mark-making procedure five times with each recipe aimed to identify potential inner variability in the efficiency of paint mixtures and to reduce chance-related results, thus conveying more realistic trends about the performance of the pictorial recipes. To make the lines, the paint was applied once in a continuous technical gesture from top to bottom, thus testing its performance through a single application act. To make the solid-infilled squares, the paint was applied repeatedly until it entirely covered the figure's area and the bedrock's surface was no longer visible, thus testing the complete performance of the paint recipe, regardless of the number of technical gestures required for its application. During this process, each recipe was classified according to its *applicability:* the ease or difficulty of applying the paint to the bedrock, measured by the greater or lesser number of technical gestures and appraised by the higher or lower technical dexterity required to stick and distribute the paint on the bedrock while achieving the desired form (in our protocol, line or square).

When the performance tests were completed, the experimental marks were stored vertically and left to dry for 6 months in a sheltered open-air space. During this time, they were monitored daily and all variations in their hue were recorded using the Pantone Formula Guide and the Munsell Soil Colour Chart (Figure 3j). After this 6-month period, all experimental marks were already dry and ready for analysis of all variables, which indicates that such period was sufficient for the objectives of this first stage of the experimental protocol. Further long-term observations will help analyse taphonomic processes, which are included as a second step of the protocol. After this monitoring period, the experimental painted marks were analysed by testing and rating each recipe according to two variables:

a) *coverage capacity*: the affordance of the paint to fully cover the bedrock forming a homogeneous colour surface with a low incidence of structural flaws, leading to a mark with a regular surface and a clearly defined perimeter;
b) *adhesiveness*: the affordance of the paint to adhere to the bedrock surface without dripping, smudging, splashing, or exfoliating.

Each set of five marks made with each recipe was scrutinised in order to grade the recipe's performance in each of the three variables (applicability, coverage, adhesiveness), as follows:

a) *high performance*: all five experimental marks in the set consistently exhibit good quality traits (e.g. homogeneity, regularity, etc.) and lack flawed traits (e.g. smudges, dripping stains, etc.,); hence, the recipe shows a high performance to achieve the feature under study;
b) *medium performance*: not all experimental marks show the same characteristics regarding a feature (e.g. only some marks of the recipe achieved good coverage);
c) *low performance*: none of the experimental marks present characteristics that indicate good performance of the recipe regarding a feature (e.g. no marks have good adhesiveness).

Any cases of functional variability of a recipe, in which it proved to be efficient for filling-in squares but inefficient for making lines (or vice-versa), were recorded and studied to assess the potential conditions for such variability. Once the three features of each recipe were rated for the lines and the solid-infilled squares sets, we carried out a functional classification by compiling all the results as follows:

1. when the ratings of three features of a set were homogeneously high, the recipe's rating for such set was considered *efficient*;
2. when the three feature's ratings were homogeneously low, the recipe was deemed as *inefficient*.

3. when the coverage or adhesiveness was low, the recipe's rating was considered *inefficient*.
4. when ratings were mixed between high and medium, the recipe was considered *partially efficient*.
5. when the ease of applicability was low, but the coverage and adhesiveness was high or medium, the recipe's rating was classified as *partially efficient*. This is because a low rating on the ease of applicability does not render the recipe necessarily inefficient: it only makes it difficult to use, and this is an operational problem that can usually be overcome through a greater labour investment and technical skill.

The last step of the experimental protocol was to compare the experimental painted marks obtained with each experimental recipe with the LRA motifs. Given the infeasibility of an in-situ comparison, this process was carried out using high-resolution digital photographs of the experimental marks and of around 1,500 rock art motifs with high conservation rates from the nine selected sites. For this analysis, the edges, ends, and internal structure of the experimental lines were compared to those of the lines of the archaeological images, which are often used to outline figures and represent details (e.g. bows, arrows, headdresses, and antlers). Likewise, the experimental solid-infilled squares were compared to the solid-infilled shapes that make up the body of the vast majority of human and animal motifs in this rock art tradition, paying particular attention to the way the paint adheres to and covers the bedrock. During this comparative assessment, the level of technical similarity between the experimental marks and the lines and solid-infilled shapes of the Levantine rock art images was classified into three different categories:

a) when all experimental marks exhibited technical features equivalent to those of the LRA sample, the experimental recipe was rated as *highly similar*;
b) when only part of the experimental marks exhibited technical features equivalent to those of the LRA sample, the experimental recipe was rated as *partially similar*;
c) when none of the experimental marks exhibited technical features equivalent to those of the LRA sample, or when the experimental recipe presented techno-morphological variability (i.e. it worked to make solid-infilled squares but not lines), the experimental recipe was rated as *dissimilar*.

RESULTS: ON PIGMENTS, BINDERS, AND RECIPES

Tables detailing the analysis and classification of the 112 experimental recipes in relation to the methodological parameters outlined above can be found in the supplementary material (Tables 4–9). Due to space constraints, this section focuses on the most relevant experimental results, which are summarized in Table 1.

Assessment of the affordance of pigments and binders and the performance of experimental paint recipes led to the identification of a wide range of results. First, attempts to paint lines and solid-infilled squares with any bare pigment (with no binder), were totally inefficient. Pigment powder has low applicability, low adhesiveness, and low coverage capacity. Blood, in turn, showed a high adhesiveness but very low applicability and coverage capacity. Both hematite and coal exhibited a proper interaction with the tested binders, resulting in five recipes (per pigment) with high-efficiency ratings (two simple-structure recipes and three complex-structure recipes). In contrast, charcoal particles interacted poorly with the binders in almost all recipes, spreading heterogeneously throughout the paint mixture and generating paints with a low coverage capacity. A similarly low performance was shown by pyrolusite, which proved to be efficient only when mixed with binders of a fatty nature in simple-structure recipes. Finally, there was only one barite complex-structure recipe rated as highly efficient, because barite did not mix homogenously with most binders; moreover, the experimental marks produced with barite-based recipes looked initially transparent and only turned white about 2 hours after the paint was applied to the bedrock.

A number of binders showed the best performance in simple-structure recipes rated as efficient at producing both solid-infilled squares and straight lines: milk (2 recipes), heated fat (2 recipes),

TABLE 1 Synthesis of the experimental results.

Experimental recipes			Solid-infilled squares						Straight lines						Comparison between experimental data and archaeological sample
				N° of recipes with high-performance rates per feature					N° of recipes with high-performance rates per feature						
Pigment	Recipe structure	N° of recipes	N° of squares	Ease of applicability	Coverage capacity	Adhesiveness	N° of recipes with high-efficiency ratings	N° of lines	Ease of applicability	Coverage capacity	Adhesiveness	N° of recipes with high-efficiency ratings	N° of experimental paints highly similar to the LRA paints
Hematite	No binder	1	5	0	0	0	0	5	0	0	0	0	0
Hematite	Simple	11	55	4	7	10	2	55	4	4	10	2	3
Hematite	Complex	20	100	10	10	17	7	100	10	3	18	3	3
Coal	No binder	1	5	0	0	0	0	5	0	0	0	0	0
Coal	Simple	10	50	4	6	8	4	50	4	2	10	2	2
Coal	Complex	6	30	4	3	6	3	30	4	3	6	3	3
Charcoal	No binder	1	5	0	0	0	0	5	0	0	0	0	0
Charcoal	Simple	10	50	1	4	7	1	50	1	0	8	0	0
Charcoal	Complex	7	35	1	1	5	1	35	1	1	5	1	1
Individual charcoal	Complex	8	40	0	0	0	0	40	0	0	0	0	0
Pyrolusite	No binder	1	5	0	0	0	0	5	0	0	0	0	0
Pyrolusite	Simple	11	55	7	5	8	4	55	7	2	11	2	2
Pyrolusite	Complex	8	40	3	2	6	0	40	3	0	8	0	0
Barite	No binder	1	5	0	0	0	0	5	0	0	0	0	0
Barite	Simple	9	45	2	3	6	2	45	2	0	7	0	0
Barite	Complex	6	30	2	2	5	1	30	2	2	5	1	2
Blood	No binder	1	5	0	0	1	0	5	0	0	1	0	0

blood (1 recipe), and egg white (1 recipe). In turn, the binders with the best performance in efficient complex-structure recipes were water + honey (3 recipes), milk + honey (2 recipes), heated fat + milk (1 recipe), water + honey + egg (1 recipe), and milk + honey + egg (1 recipe) (see details in Supplementary Material). Thus, honey, milk, water, heated fat, and egg were classified as the most effective binding substances in our experiments. However, some of these materials are only efficient when treated via very specific technical processes (see Supplementary Material–Additional information on the affordance of the binders).

Out of the 51 simple-structure recipes, five were classified as efficient (9.8%), whereas eight of the 55 complex-structure recipes achieved this rating (14.5%): this entails that, in spite of requiring a higher labour investment, complex-structure recipes have a slightly higher tendency to afford better results than simple-structure recipes during the image-making process (Table 2). Concerning the ratings of recipes to produce experimental marks, we found that simple and complex recipes (N = 112 recipes) have the same *ease of applicability* to produce squares and lines, which entails that each recipe usually had no differential performance when applying paint as a narrow stripe with a single stroke or when paint via several strokes to make a solid figure. In terms of *coverage capacity,* we observed two main tendencies: (1) 73 recipes have the same coverage ratings to produce squares and lines, (2) 39 recipes have a higher rating to produce squares than to produce lines; this second tendency is related to the fact that it was possible to cover an area by repeating the technical gesture of paint application as much as required, although it was not possible to paint a proper straight line with a single stroke if the recipe had a low level of coverage efficiency. Regarding the *adhesiveness*: (1) 102 recipes have the same ratings to produce squares and lines, (2) 10 recipes have higher ratings to produce lines than to produce squares; this is because although adhesiveness depends on the technical characteristics of the paint recipe and on the type of bedrock, the accumulation of greater amounts of paint on the solid-infilled squares increased the chances of smudges, splashes, and dripping (see Supplementary Material–Tables 4–9).

DISCUSSION: DISENTANGLING TECHNO-VISUAL AFFORDANCES AND LABOUR INVESTMENT IN LRA

Experimental archaeology develops technical processes under controlled conditions in the present in order to analyse unknown details of material culture that was produced and used in the past (Morgado et al., 2011). Experimentation and the archaeological record are dialectically connected, because the research questions that arise from the archaeological evidence guide and determine the design of the experiments, whereas the experimental results provide new and independent information—for example, diagnostic criteria—which help build deeper insights about the archaeological record (Álvarez & Fiore, 1995, p. 217). Thus, using experimental data as analytical parameters with independent validation, we applied them to our LRA sample to establish empirically supported inferences about its production process.

Out of the whole set of 112 *experimental recipes*, we identified a total of 16—7 simple-structure and 9 complex-structure recipes—that generate highly similar paints to those used to produce LRA (Table 2; Figure 4). Regarding *colour*, although it is not possible to assume that archaeological images have kept their original hues (due to weathering/taphonomic factors), it is interesting to note that the hues of the experimental marks made with these 16 recipes fit in the chromatic range documented in our study area and are *highly similar* to the LRA motif's colours. Using these 16 recipes, it was possible to produce squares with a homogeneous paint layer that shows a low incidence of structural flaws and no smudges, splashes, or drippings, *highly similar* to the filling observed in figures of the archaeological sample, such as the red deer painted in Cova dels Cavalls (Figure 4a and b) or the black human figures represented in Cova Remígia (Figure 4c and d). Moreover, we should emphasise that most flaws currently seen in the rock art images are not related to the paints' technical qualities but are instead a consequence of degradation processes that affect the bedrock, such as weathering, erosion, and vandalism. Also, using these experimental recipes, we produced lines with straight

TABLE 2 Simple and complex-structure experimental recipes that generated paints highly similar to those used to produce Levantine rock art.

Red (hematite)	
Simple-structure recipes	1 g hematite + 1 ml milk
	1 g hematite + 1 g heated fat
	1 g hematite + 1 ml egg white
Complex-structure recipes	1 g hematite + 1 ml water + 1 g honey
	1 g hematite + 1 ml milk + 1 g honey
	1 g hematite + 1 ml milk + 1 g honey + 1 ml egg
Black (pyrolusite)	
Simple-structure recipes	1 g pyrolusite + 1 g heated fat
	1 g pyrolusite + 1 ml egg white
Black (charcoal)	
Complex-structure recipe	1 g charcoal + 1 ml water + 1 g honey + 1 ml egg
Black (coal)	
Simple-structure recipes	1 g coal + 1 g milk
	1 g coal + 1 ml blood
Complex-structure recipes	1 g coal + 1 ml water + 1 g honey
	1 g coal + 1 ml milk + 1 g honey
	1 g coal + 1 g heated fat + 1 ml milk
White (barite)	
Complex-structure recipes	1 g barite + 0,5 ml water + 1 g honey
	1 g barite + 1 ml latex + 0,5 ml water + 1 g honey

edges, regular ends, and uniform inner structure, even when the bedrock's surface was irregular: these visual-technical characteristics are *highly similar* to the lines used to silhouette and infill the black deer painted in Coves de la Saltadora (Figure 4e and f), to create the body and the bow of black archers represented in Cova del Civil (Figure 4g and h), and to paint white details in red human figures of this site (Figure 4i and j). In sum, our results show that all pigments identified by archaeometric studies in different LRA samples have been experimentally tested as viable colouring substances in the production of paint. Moreover mineral charcoal, which had only been inductively proposed as a viable pigment, has been tested as highly useful to produce black paint.

Regarding the *binders* used in these 16 experimental recipes, our findings correlate with some data obtained through physicochemical analyses on LRA located in the study area. First, given that all "bare pigment" recipes (prepared without binders) proved to produce rather *dissimilar* marks than the LRA images, we can infer that the LRA of the Maestrazgo region and surroundings is likely to have been produced with paint recipes containing binders. Thus, when archaeometric studies of paint samples do not show traces of such elements, this is probably due to decay/evaporation processes. Secondly, some specific archaeometric cases are *highly similar* to the experimental recipes. For example, the black figures of Les Dogues—located in our study region—seem to have been produced using a mixture of charcoal and animal fat or honey associated with water or milk (López-Montalvo et al., 2017), a very similar combination to the only charcoal-based experimental recipe [R = 1 g charcoal + 1 ml water + 1 g honey + 1 ml egg] that we consider technically similar to the Levantine sample. Furthermore, the analyses carried out on the red paintings of Coves de la Saltadora (Roldán et al., 2018) are also compatible with the experimental data, because in three of the six red recipes classified as *highly similar* to the archaeological cases, milk was used as a binder. In sum, out of the binders proposed inductively in the LRA literature (water, saliva, blood, animal fat, egg white, honey,

FIGURE 4 Example of comparison between the experimental marks and the archaeological sample. (a) 1 g hematite + 1 ml milk; (b) detail of a red deer painted in Cova dels Cavalls: (c) 1 g charcoal + 1 ml water + 1 g honey + 1 ml egg; (d) black archers painted in Cova Remígia (charcoal-based pigment, according to Lopez-Montalvo et al., 2014); (e) 1 g pyrolusite + 1 ml egg white; (f) detail of a black deer painted in Coves de la Saltadora (produced with manganese oxide, according to Roldán et al., 2007) (g) 1 g coal + heated fat + milk; (h) black archer painted in Cova del Civil; (i) 1 g barite + 0.5 ml water + 1 g honey; (j) white details painted in Cova del Civil.

resin, and plant latex), our experimental results show that saliva, resin, and latex are not compatible with highly efficient paint recipes (the only exception being latex in a barite complex recipe).

Analyses of the cost of the technical operations through which raw materials were obtained and transformed to produce paint, sustain inferences regarding the labour investment related to the creation of rock art (Fiore, 2007). In our case study, both pigments and binders used to prepare the experimental recipes can be easily gathered within the Levantine territory: it only requires an in-depth knowledge of the local plant, animal, and mineral resources. Occasionally, colouring materials are available in the surroundings of the rock art sites: This is the case in Cova del Cavalls, where iron oxide can be found in rock formations a few meters from the shelter. Hence, without excluding the possibility that symbolic and cultural constraints might have conditioned the use of raw materials obtained in specific deposits, we can suggest that, in a prehistoric scenario, the procurement of pigments and binders required a comparatively low labour investment and that it may have even been carried out during other activities like hunting or food gathering, using an "embedded strategy" (Binford, 1979). In turn, the labour investment related to the paints' production must have varied according to pigment hardness, because labour invested in grinding materials increases with their hardness. Our experiments show that, to reach a suitable granulometry (between 20 μm and 100 μm), work on pigment grinding ranges from 20 minutes on average to powder a 10 g fragment of barite to 45 minutes on average to powder a 10 g fragment of pyrolusite (Santos da Rosa, 2019a). Hematite rocks took between 30 and 40 minutes (see Supplementary Material–Additional information on the time required to process the pigments, Table 10). Likewise, the preparation of complex-structure recipes would demand a more significant labour investment compared to simple-structure recipes, because the former involves the procurement and processing of a greater quantity and variety of raw materials, entailing longer operative chains, composed of more stages (Fiore, 2007).

It is also interesting to note that our experimental results show that painting lines required only 0,1 ml. of paint, whereas painting the squares required 0,1 ml. (single coat of paint) or 0,2 ml. (two or more coats of paint). The projection of these results to LRA indicates that small-sized and medium figures such as those commonly found in LRA would have required no more than 0,2 ml. of paint (of any recipe) and that larger ones would have required 0,5 ml. at most (Santos da Rosa, 2019a). This entails that although paint recipes required a significant labour investment in their production stage, they had very high economic yields in their use stage. Hence, it is not very likely that prepared paint was stored, because not many quantities were required to produce whole rock art panels; however, it is expectable that raw pigments were stored in order to avoid wasting the labour invested in their procurement and grinding, and that they were retrieved to mix them with binders when necessary.

Experimental data also reveal that the degree of technical skill required to use a specific recipe is directly related to its ease of applicability. The viscosity of certain pictorial mixtures causes the paint to stick to the active zone of the brush, making it extremely difficult to apply it to the bedrock surface and to create lines with precise edges. The use of these recipes requires greater technical skill and labour investment, because more careful and precise gestures are involved, requiring more time and dexterous hand-eye coordination, to properly complete the technical operation. Among the 16 recipes rated as *highly similar* to the LRA study sample, two were classified as *partially efficient* precisely due to their *medium ease of applicability* [R = 1 g hematite + 1 ml egg white; R = 1 g barite + 1 ml latex + 0.5 ml water + 1 g honey], because their use in experimental image making was not straightforward and required extra technical gestures to correct the flawed painting strokes (none of them is compatible with LRA archaeometric results). Conversely, the other 14 were *efficient* recipes with high applicability ratings: Out of these, two (1 g charcoal + 1 ml water + 1 g honey + 1 ml egg; and 1 g hematite + 1 ml milk) are compatible with the LRA archaeometric results (López-Montalvo et al., 2017; Roldán et al., 2018).

Bearing in mind that the creation of rock art encompasses an economic effort that is justified by the importance that the images acquire within the societies in which they were conceived (Domingo, 2005), the experimental results allow us to suggest that, in some specific cases, Levantine painters could choose paint recipes that demanded a higher level of technical skill during their use, but which also had a high techno-visual affordance, allowing the production of detailed motifs with seamless surfaces and flawless edges. Such technical choices would have prioritised the visual aesthetics of the paint recipe over the labour investment necessary for its use.

CONCLUSIONS: SHEDDING LIGHT ON ROCK ART PRODUCTION VIA THE PRODUCTION OF EXPERIMENTAL ROCK ART

After more than a century of inductive inferences, the methodological approach developed in our research made it possible to obtain independent criteria to test the validity of the main assertions concerning the Levantine pictorial recipes. Experimental results have documented that each pigment and each binder have different technical affordances, which lead them to interact in very specific ways when mixed in recipes. Experimental parameters strongly suggest that rock art production in the Maestrazgo region and its surroundings required the use of paints composed of pigments and binders, which are compatible with those locally available. In turn, experimental recipes have shown that it is possible to paint with almost any pictorial mixture, yet not every recipe has the same performance: This is the reason why only 16 of 112 recipes had the required techno-visual affordances to produce experimental marks *highly similar* to those observed in the LRA.

The results presented in this paper highlight the potential of experimental research as a way to approach technological and economic processes that underlie the creation of prehistoric art. As shown in our case study, only a few simple and complex experimental recipes are compatible with the degree of techno-visual detail required to produce LRA. This leads us to suggest that LRA production required the appropriate technical means that could reliably transfer the person's skill from his/her body to the bedrock, thus affording the desired quality of the image. Such means may have been chosen even if their preparation entailed more work, because what led the producers seems not to have been a cost–benefit logic based on saving time, energy, or labour but rather a logic based on maximizing a wealth of visual detail.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Repositori Institucional URV at https://repositori.urv.cat/fourrepopublic/search/item/TDX%3A2993, reference number TDX:2993.

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SUPPORTING INFORMATION

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