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Gazed Pottery: an Archaeometric-Cognitive Approach to Material Culture Visuality

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ABSTRACT

This paper presents a study of visual perception through the application of eye-tracking of prehistoric ceramics. The study is a feasible methodology to understand the agency of material culture through quantitative techniques, which allows for the analyses of possible relationships between visual-perceptual behaviour, material culture and social complexity. In particular, the horizontality of gaze is shown to be associated with pottery from early periods and its verticality increases in pottery materials from later, more complex societies. These, and other results, confirm that differential patterns of visual response by observers are determined by the material characteristics of each ceramic style. Implications for improved interpretation of archaeological phenomena are discussed including the possibilities of new applications for heritage management. Therefore, eye-tracking analysis appears to be a powerful and profitable archaeometric technique.

1. Research problem: towards an archaeology of visuality

A fundamental facet of humankind's relationship with the world, with things and with other beings is seeing. What we see, how we see it, how we are seen by others, how we react to what we see or when we are seen. If everything that is visible is symbolic (Criado-Boado, 1993, 1995), this entails that the self, social identity, community, the built environment and symbolic meaning are all related to visuality. Visuality, even taking into account the criticisms levelled against ocularcentrism (Levin, 1993), is a central issue for humans and thus for research.

Understanding the arrangement and social meaning of e.g. architecture, urban settings, the landscape, or bodily practices (adornments or tattoos), requires us to carry out different sorts of visibility analyses. But do we really understand everything that "visibility" implies as a social, symbolic and cognitive process, what the relationship between these processes is and how material culture affects or even produces visuality?

Cognitive archaeology and anthropology have already shown that large shifts in historical or ethnographic societies have provoked major changes in terms of perception and cognition (Malafouris, 2013). For historic art styles this has even been accounted for by cognitive sciences (GrahamRedies, 2010). An accurate account of the form and rationale of interaction between social, stylistic and cognitive changes is difficulted by the divide between disciplines and the specific know-how required for the study of historic or archaeological periods. In order to consider cognitive issues in the past, it would be required to produce reliable data for this research. Precisely to attain this, in the present study a synergic alliance between archaeology and cognitive sciences (Renfrew et al., 2009) was undertaken.

Cognitive studies in the humanities, cognitive archaeology, and before all of this, philosophy and phenomenology have dealt with issues of visuality and perception. This body of work is essentially reflexive and speculative, in the best tradition of the humanities. Sensible interpretations are offered, based on transferring the most advanced results of cognitive sciences to archaeological and anthropological case studies. In archaeological research, these issues have been studied mostly in relation with human evolution, maintaining a very long-term perspective (e.g. Haidle, 2010; Haidle et al., 2015). However, by

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addressing the topic in more recent chronologies an approximation to the sapient paradox is permitted (Renfrew et al., 2009: 1935), finding the "tracer" that Malafouris (2013) wisely demands for demonstrating the material engagement of mind. The possibility for this dynamic and more innovative approach was already anticipated in Wells (2012), by using solid data and applying a new set of methodologies. These then contribute to implement the "spatial turn" (Earley-Spadoni, 2017) on archaeological visual analyses. Through the proper study of perception itself, the overly descriptive and insufficiently transparent phenomenological approaches (Bernardini et al., 2013) or the GIS quantitative approaches to the effects of perception (Paliou et al., 2011; Eve and Crema, 2014) are overcome.

Often these aims lack data or methodological tools that could be used to construct any type of "evidence" (a cutting edge of the archaeological method, as argued by Chapman and Wylie, 2015). What is put forward in the present work is that archaeometry could make a major contribution by a "more integrated approach" (Martlew et al., 2008; Torrence et al., 2015) and linking archaeometric approaches to the social dimension (a "social archaeometry", Jones, 2004; Martinón-Torres, 2008). Drawing on this reflexive archaeometric agenda, the present article aims to present its contribution to this. Following the science-orientated revolution in archaeology (Kristiansen, 2014), scientific methodologies and techniques are brought together in this work. To explore the very possibility of providing archaeometric data to sustain cognitive research. In order to overcome simplistic theoretical divides this is necessarily combined with reflective and interpretative research. Phenomenology and a critical use of technology are applied in the search for a new positive synthesis of systems to produce new knowledge.

This article aims to address the possibilities of the mentioned synergic alliance between archaeology and cognitive sciences, and detail its contribution. In an approximation to this topic, the gaze from the perspective of material culture is examined here, implementing eye-tracking analysis (ETA). The fundamental research questions are: Is there any chance to approach the visuality of material culture from an archaeometric perspective? If so, how could an archaeometric-cognitive approach to material culture enhance our knowledge of visual perception? And thus, what can we learn about material culture, the processes of materialization, human life and the mind itself? (DeMarrais et al., 2005; RenfrewMalafouris, 2010). The first results of this research were recently presented in Criado-BoadoAlonso-Pablos et al., 2019). In the following pages we wish to dig into the methodologic and technical issues of this research to foster the use of eye-tracking in archaeometric research.

2. Theoretical remarks and working hypothesis on visual responses to materiality

For many years, theoretical developments have been focused on the polarisation between processual archaeology and post-processual archaeology. The intertwining of the archaeometric tendency on the one hand, and new heritage politics on the other ruled the archaeological debate over the past 30 years and changed the discipline. Meanwhile the most dogmatic aspects of this confrontation have been overcome, making it possible to integrate contributions from both fields in positive approaches. Thus, at the same time as their differences are softened, an emerging paradigm gradually begins to take shape (Kristiansen, 2014). The construction of this new disciplinary consensus is supported by the greater degree of reflexivity embedded in archaeological practice (Criado-Boado, 2016), in the best legacies of post-processualism. Rigorous methodologies and solid data, as a result of the development of archaeological sciences and processualism, are the base for this consensus. Such a positive combination of both traditions could pave the way to a much-needed objectivity, capable of contesting current trends in fake science and alternative rights (González-Ruibal et al., 2018).

These developments, fostered by an interdisciplinary debate with philosophy, anthropology and other social sciences, have balanced out the emphasis in epistemology and representationalism towards an object-oriented perspective, leading to a growing interest in material cultural studies (Brown, 2004), new thing-theory (Boivin, 2008; Alberti et al., 2011) and social ontology (Ihde, 2002; Gosden, 2008). This leads to the synthesis that, as Olsen and WebmoorWitmore (2012) put it, "archaeology is first and foremost a concern with everyday things". Recent developments in the field of cognitive archaeology (Renfrew, 2010) clearly confirm this direction and detail the resulting problems. As this synthesis refers to a processual genealogy, it deals with research problems that post-processualism has partly forgotten or ruled out: it seeks out a large, evolutionary perspective, capable of systematically accounting for characteristics of humanity and human life. In this context, we can now encompass an integrated approach to human engagement with material culture and technology and with the evolution of the human species and its capacities (Mithen, 1996; Thornton, 2012).

These insights have focused on the agency of material culture as a new research priority: how it operates, which effects it produces, and what its relationship with other agents is like (Knappett, 2005). This reiterates the physical world, not as an external setting of human history, but instead as a medium that interacts with social and individual histories. Agency refers to the basic capacity that organisms have for causing changes in their environment (Johannsen et al., 2012). Material agency, then, is not an isomorphic extension of human agency (Heidegger, 1994; Malafouris, 2013) but rather "active in the manner of objects" (Gosden, 2001). Objects hold a function that goes beyond being a mere instrument. The term can be applied only if "instrument" is understood as something that is embodied in humanity itself, and through which the environment is modified (Ingold, 2000). Overcoming reductionist models, based on brain/body or mind/brain dualities, cognitive sciences now assert that the brain and the body are extended in instruments and therefore extend into the world (Dunbar et al., 2010). The relation of the hammer to the carpenter, the biface to the hominid (Knappett and Malafouris, 2008), or the basket to its maker (Ingold, 2011), could be considered just as intimate and embodied as the cane is for a blind person (Merleau-Ponty, 1962 [1945]) or a prosthesis for a disabled person. However, from the Humanities these topics are often approached in a purely narrative, qualitative and speculative manner. Therefore, the new thing-theorists, onticologists (Bryant et al., 2011) or, quite paradoxically, the processual-cognitive partisans (Renfrew, 1994) often lack empirical method and data (Thornton, 2012: 2036).

Considering that material culture is something that embodies human action and materializes the human mind, the cognitive mechanisms of (visual) perception permit the identifying of relationships between mind, world and matter. This relies on the fact that visual perception does not occur mainly in the retina, but in the brain involving high level cognitive functions (such as context, abstractions, concept formation, linguistic meanings, memory, illusions, active interference: Bar 2004; Geisler 2008; Constant et al., 2022; Clark 2022; Quian Quiroga 2012; Cami et al., 2020). Taking this into account, a valuable question is to ask to what extent the outside (visual stimuli) interacts with visual cognition. In order to address this, we assess visual perception and the corresponding cognitive mechanisms by concentrating on visual stimuli and their changes. Visual perception is not disembodied (Braidotti, 2006) but embodied, combined with emotion, memory, and motion (Bagnall, 2003; Thrift, 2004; Hutchins, 2010; Jones, 2005; Stafford, 2001). Interestingly, it should be even considered highly enactive due to the ocular motions (Nöe, 2004). Not only is the entanglement of humans, things and the world (stated by Hodder, 2012) exemplified in this direction of research, it also bridges culture, biology and matter. The *transitive engagement* of visual perception in a world of objects has been remarked upon in different domains; for example, critical museology posits the existence of a two-way interrelationship between the observer, and the observed object (Bagnall, 2003; Thrift, 2004). The statistics of the world that influence/affect human perception do not

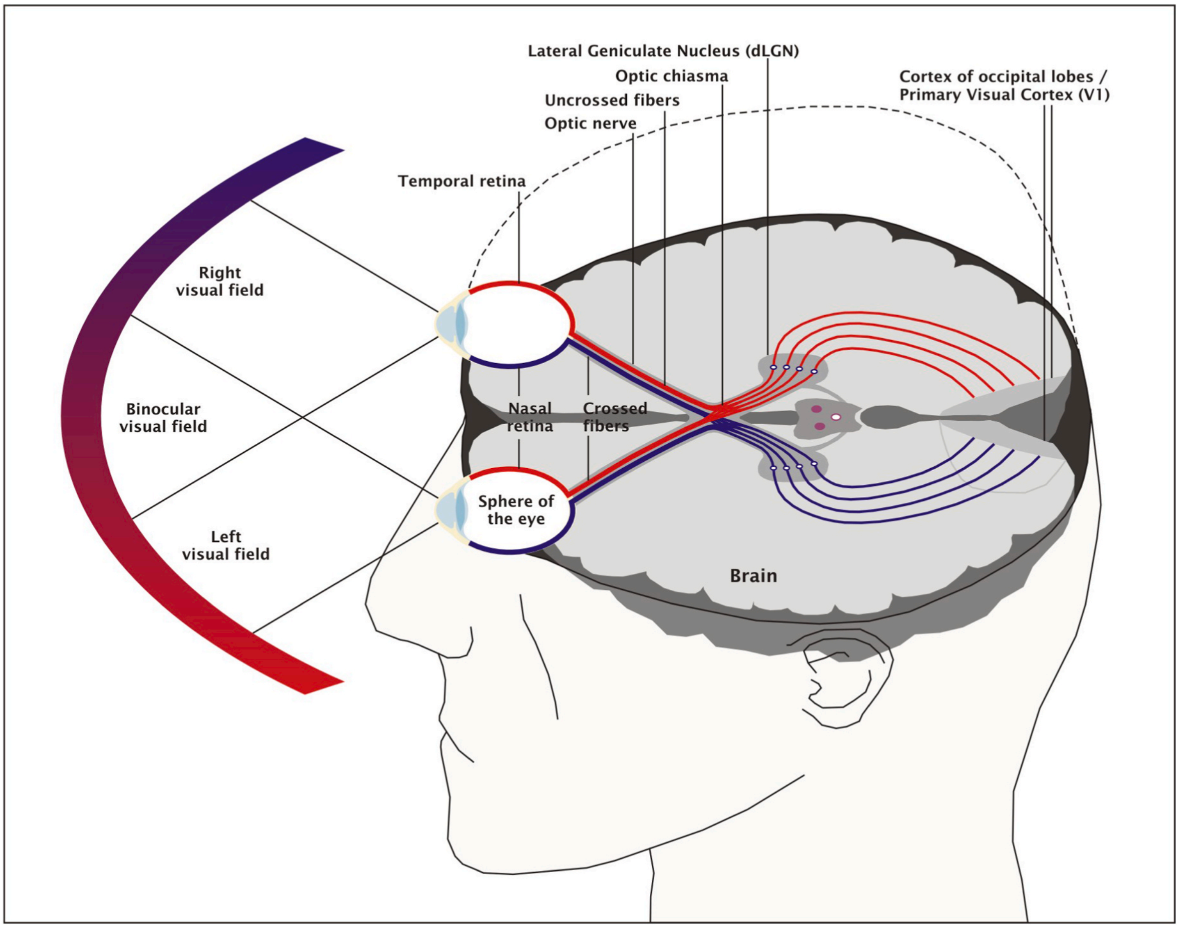

Fig. 1. The visual perception is the result of a process in the brain which decodes the electromagnetic signals from the world, including eye movements, the filtering introduced by the retinal mosaics, and the specific processing performed by a hierarchy of different brain nuclei and cortical areas.

only include the natural world, but also embrace the artificial (Graham et al., 2010).

As a result, the way of looking is a powerful proxy of testing hypotheses about the visual statistics of the world. We put forward that at least one of the "tracers" Malafouris (2013) demands for demonstrating the material engagement of mind, is the pattern of visual behaviour. This behaviour links the gaze of the external world with the visual part of the brain through oculomotor movements (Fig. 1). This can be easily studied with eye-tracking analysis (ETA) techniques and equipment. This approach investigates the fundamentals of visual perception in relation to its cognitive nature, which will be demonstrated as feasible in archaeology in the following pages. The working hypothesis we will review is that the physical features of a material object predefine the way the object will be explored by the observer. This transcends the basic notion of mere saliency, which predicts which areas are most frequently visited by the gaze as they hold for example key informations. This work presents the thesis that the object itself drives the visual behaviour to such an extent that this can be predicted from the materiality itself. Visual behaviour (ie. eye movements) is explored as the cognitive response to external stimuli: materiality imposes a tendency in movement, to which visual cognition reacts driving an oculomotor feedback. Hence, the analysis of visual movements by ETA data would allow us to observe the effect of materiality in the perceptual-cognitive processes. We can learn about the pattern of the material culture, but also about the capacities and functions of cognition.

The way in which eye-tracking analyses have been previously used, also in different fields of humanities (art history, visual studies, marketing and archaeology), has been limited to the question what we see. The approach presented here is highly innovative and therefore able to contribute data to a wider field of research, as it asks not what, but *how* we see. In the answer to this question, and explaining why this is so, lie unprecedented possibilities not only for approximations to archaeological questions, but also further understanding in cognitive sciences.

3. Materials and methods: eye-tracking of archaeological material culture

Eye-tracking is a technique that until recently was not sufficiently exploited in many fields. It was refined by Yarbus (1965–1967) (Yarbus, 1967), following early research from before the Second World War. This methodology was abandoned when psychology replaced its interest in mental processes (such as perception or attention) by a behavioural approach, then at the end of the 1960s again replaced by cognitivism. ETA has become increasingly important, with an exponential growth in its applications, impulsed by its robustness (see Holmqvist et al., 2011) and the availability of more versatile, powerful and economical equipment. Nowadays, ETA is being rapidly implemented in many different domains and in diverse hardware (including smartphones) to promote a friendly interaction between the user and the machine. Numerous studies have applied the use of ETA to artistic paintings, starting with Buswell (1935), the first systematic study using ETA in the world of art. It was then widely used in art by psychology (eg. Kapoula et al., 2010; Segev et al., 2014). Nevertheless, the main focus of this research has always been on studying the mechanisms of visual perception, and not learning about art or material culture in itself, or about their relationship with humans and the mind.

Therefore, as the use of ETA did not become widespread until the mid-1990s; more than 90% of the ETA publications correspond to the

Ca. time period (cal BC)	Settlements			Monumentality		Burial practices		Production				Environmental impact	
	Location	Form	Mobility	Where	Degree	Form	Type	Main productive activities	Storage capacity	Metallurgy	Long distance trade	Degree	Trend
Before 4500	Uplands	Camps	Constant	Absent	Null	Unknown	Unknown	Hunting Gathering Horticulture	Null	Absent	Null	Null	-
4500 – 2700	Uplands and lowlands	Camps Small open villages	Important (Seasonal?)	Burials	Big to extreme	Megalithic mounds	Collective	Slash and burn agriculture	Very low	Absent	Increase	Low to moderate (deforestation, soil erosion)	Increases
2700 – 2300	Mainly lowlands	Big enclosed villages	Low	Ceremonial	Medium	Varied (mounds, cists, pits)	Individual	Fallow agriculture	Big	Emerging	Increase	Low to moderate	Increases
2300 – 1200	Uplands and lowlands	Small open villages	Important (seasonal)	Burials	Very low	Varied (mounds, cists, pits)	Individual	Stockbreeding Fallow agriculture	Low	Modest and stable	Decrease	Strong (+ soil acidification)	Decreases
1200 – 800	Lowlands	"Pit fields"	Low	Absent	Null	Varied	Individual	Fallow agriculture	Very big	Intense (x10) Specialized Large axe hoards (often as-cast)	Increase	Very strong (+metal pollution) Peak c. 1000 BC	Increases
800 – 500	Upper limit of lowlands	Small hillforts	Null	Settlement	Big (widely based on natural features)	Unknown	Unknown	Fallow agriculture	Low	Modest Domestic Large axe hoards (often as-cast)	Decrease	Strong	Holds
500 – 200	Lowlands	Small to medium hillforts	Null	Settlement and household	Big	Unknown	Unknown	Intensive agriculture	Big	Intense Specialized	Increase	Strong	Increases
200 – 0	Lowlands	Small hillforts and Oppida	Null	Settlement and household	Extreme	Unknown	Unknown	Intensive agriculture	Very big	Very intense Specialized Gold jewelry of high quality	Increase	Very strong (+metal pollution)	Increases

Fig. 2. The socio-cultural scenario of our empirical sampling; see Parcero-Oubiña et al. (2013) for a discussion of the social context and through time dynamics embedded in these chronological stages.

last 25 years. It seems to be too recent to allow for an adaptation by archaeology. This, and the lack of consistent research questions, made that ETA was not used in archaeological or material culture studies. As a matter of fact, only a single paper before 2019 on ETA applied to archaeology comes to mind (Tokitsu, 2004). This study was carried out with the purpose of monitoring the differences between skilled experts and novices while observing pottery, following a wholly different research orientation from what informs our approach here.

In order to understand our approach, it is necessary to start by stating that eyes never stay still. The phases of alleged immobility, which are called fixations, last on average 330-180 ms (Rayner and Castelhano, 2007). But even during fixations, the eyes are constantly in motion. There are four types of eye movements: saccades, micro-saccades, drifts and tremors. Saccades are rapid eye movements, from one fixation point to the next. Micro-saccades are a type of saccade of smaller amplitude and, as saccades, they are usually binocular and have comparable amplitudes and directions in both eyes (Martinez-Conde et al., 2004). Unlike saccades, micro-saccades only occur during visual fixations and, together with ocular drifts and tremors, are collectively known as fixational eye movements. Drifts are very slight, slow, and smooth random eye movements characterized by often erratic changes in direction. Ocular tremors, on the other hand, are a constant flicker of the eyes, 40–100 Hz in frequency, and miniscule amplitude. Fixational eye movements seem to play a role in processing high spatial frequencies for perception of fine detail, and, more generally, in preventing the visual world from fading during fixations. The processing of visual information mainly occurs during fixations on salient areas of the image while other regions of interest are simultaneously being identified for subsequent direct exploration. During saccades, the brain blocks visual processing to prevent the visual gap in perception and blur of the image due to their large amplitude and high velocity (Martinez-Conde et al., 2004).

In this ETA study, both saccades, including micro-saccades, and ocular drift were analysed. Saccades can follow any direction and adopt any length. The quantitative analysis of saccades is a superb way to characterize the visual exploration of an image by observers. The analysis of the distribution of the saccades' angles is a powerful tool to reconstruct the visual exploration and allows comparisons between observers and images. Drifts were also considered in this research but we concluded that they are primarily a movement that serves to predefine the fixation: since the results from their analysis fitted well with those provided by the saccadic movements and did not provide further substantial information, this paper is based mainly on saccades, and further information on drifts is provided as Supplementary Material.

The experiment proposed in this article was designed to underline the value of eye-tracking analyses in archaeology and the implications for cognitive sciences that can be derived from this. In order to do so, the posed research question to which the previously detailed approach was applied, refers to the topic of visual perception of materiality. It is stated that different landscapes can be related to different forms of seeing and perceiving the landscape (Criado-Boado, 2000). This same tendency can be observed for rock art (anticipated in Criado-Boado and Penedo, 1989, and developed in Santos-Estévez and Criado-Boado, 2000, and Santos-Estévez, 2010). For ceramics, this observation even holds conjunctural observations regarding patterns of change that can be observed over time in both the material and the society it pertains to. Archaeological hypotheses from other works (Prieto-Martínez and Cobas Fernández-Criado-Boado, 2003; Prieto-Martínez and Santos-Estévez, 2009, Bradley, 2012; Criado-Boado, 2014) suggest that over time a 'gradual transition from the predominance of a horizontal to a vertical gaze' took place. Characteristic of the societies, especially social complexity, to which the material styles belong correlate with this transition. This underlines that visual response is analogous to material styles' spatial articulation. This feeds the hypothesis that 'ways of looking, doing (style) and living (society) are inextricably related' to each other (Millán-Pascual et al., 2021).

It was decided to perform the experiment detailed in this paper using pottery from Galician (NW Iberia) prehistory and protohistory. This medium is viable for the purpose of the study as pottery spread over a long period of time. We took a set of ceramics ranging from 4000BCE −0, embracing a significant time span ranging from the middle stages of the Neolithic (Megalithism) through to the end of protohistory. These ceramics cover a variety of socio-cultural forms, from simple

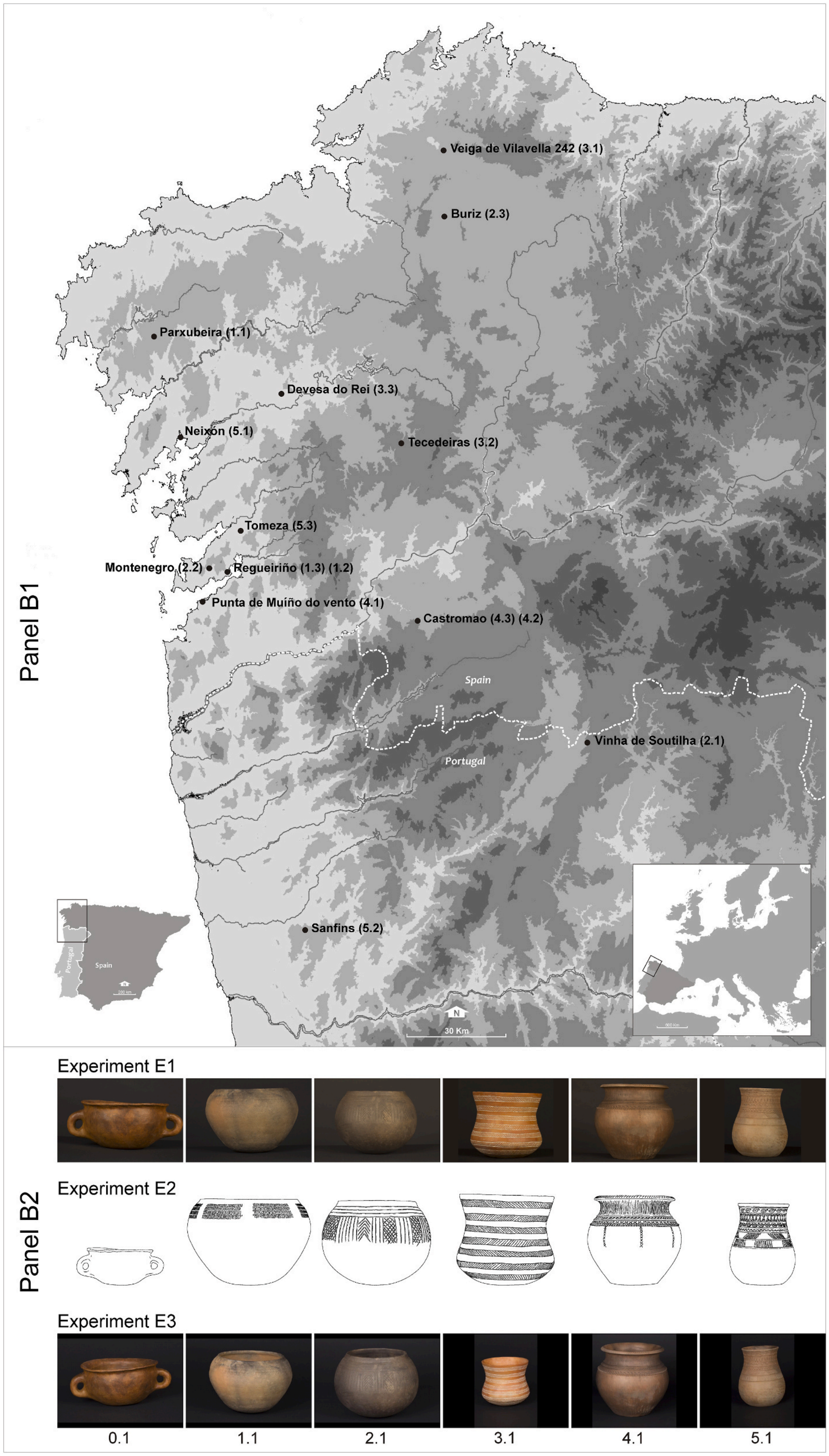

Fig. 3. Panel 2.1: Map with the location of the archaeological sites of the studied pots. Panel 2.2: Images presented in Experiments E1, E2 and E3.

communities based on the house and the family which are relatively egalitarian and building communitarian (Whitehouse and Kirleis, 2014), through to social formations based on hierarchisation, ranked societies, warriorship, aristocracy and finally complex proto-states social formations (Fig. 2, see Parcero-Oubiña and Criado-Boado, 2013). In the experiment detailed below, the visual and perceptual reactions of a vast number of experimental participants (far from what is usual in cognitive or psychological experiments) to this material culture were recorded.

The sampling of most representative vessels for each defined period was critical, considering that only a limited range of images (a maximum

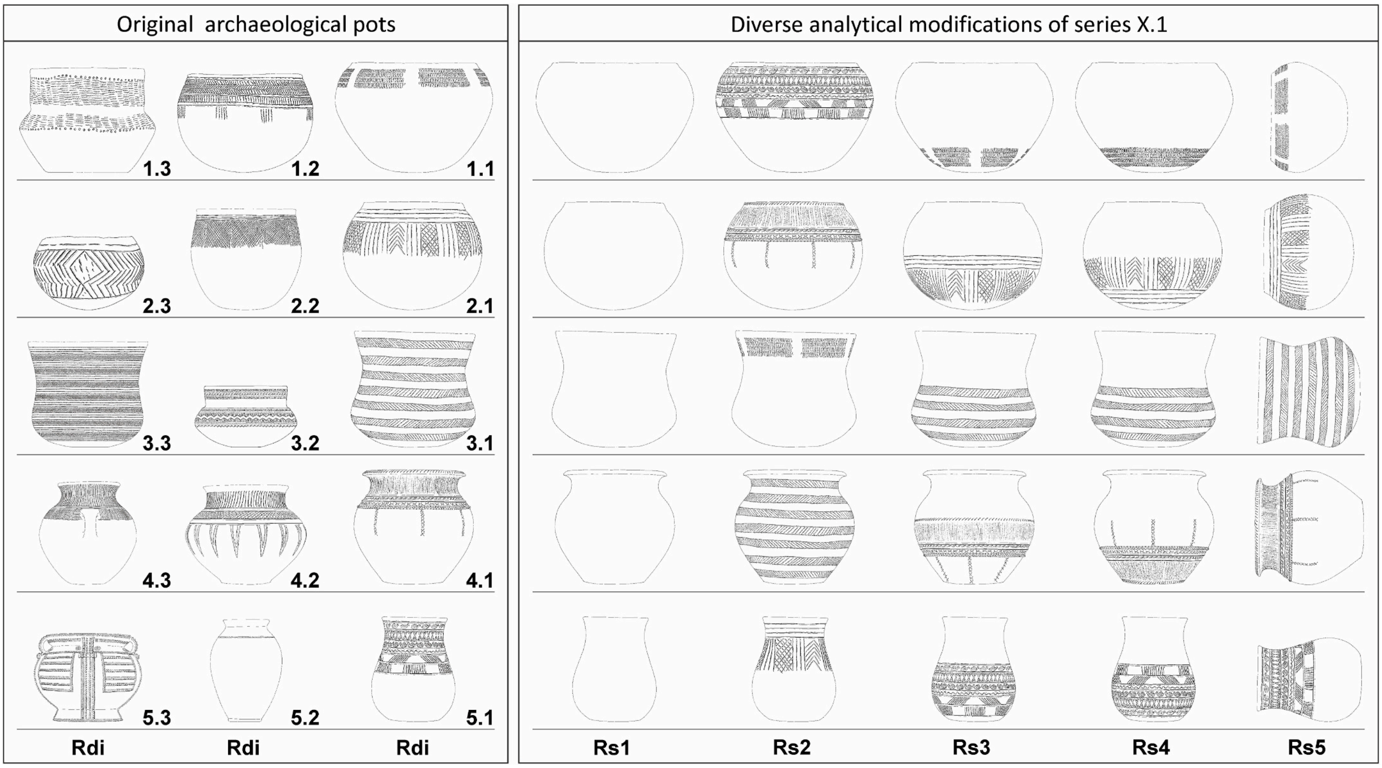

Fig. 4. Images presented in Experiment 4 (E4). The fifteen original pots are labelled as 1.1., 1.2 …, where the first digit is the archaeological period. Series artificially modified to check changes in visual response, are labelled to facilitate the identification of their analytical results.

of 30–40 images/experiment is recommended) can be presented to volunteers because effects of fatigue, adaptation and lack of attention. Fifteen pots were chosen, three representing the formal variety of each one of the five main Galician prehistoric ceramic styles: Middle Neolithic, Late Neolithic (Prieto-Martínez, 2017), Early Bronze Age (ie. Bell Beaker pottery, Prieto-Martínez, 2009), Middle Iron Age and Late Iron Age (González-Ruibal, 2004) (Appendix B Figss. 1–5).

Replicas of the pots were made for the purpose of the experiment, the process of which in itself was an experimental archaeology project (see Supplementary material). For operational reasons, instead of carrying out the analysis using physical pieces, high resolution photos were presented on a computer-controlled monitor. Certainly, it is desirable to record normal observation conditions and to account for the differences between observing material culture (3D objects) and 2D images (as paintings, drawings or monitor images). However, for now the focus lies on studying the dynamic of visual exploration. Thus, a good starting point is to work with on-screen images, as most ETA does: whatever is lost by altering the "ecological" observation conditions is recovered by having greater control over the data.

Eye movements were collected using an Eyelink II (SR Research Ltd., Osgoode, Ontario, Canada) 500 Hz eye tracker. It records both eyes independently, at a sample frequency of 500 Hz. Each sample/measurement includes the spatial position of the centre of the gaze (recorded in X–Y coordinates) and the pupil size. The saccade velocity is inferred from the shift of positions over time. Based on this, analyses were carried out in order to determine: saccade directions; saccade velocity; fixation duration; average distance of fixations to the centre; probability, range, amplitude, and peak velocity of horizontal and vertical saccades; landing of first saccade; latency, amplitude, and peak velocity of first saccade; pupil diameter; heat maps (mapping of eye visit distributions on pots); micro-saccades; and several parameters of drifts (ie. slow eye movements). A great amount of information was generated, which facilitated complex analysis. Differences in terms of gender, age and sample population were considered for all of the variables (see Supplementary material). The presentation of stimuli and coordination between the registration system and the presentation system was implemented in MATLAB based on the Psychotoolbox and the specific toolbox for Eyelink. Data were processed with nonparametric statistics, in particular with the Kruskal and Wallis test.

It is known from other studies that the most common saccades angles in free-viewing tasks are distributed around the horizontal or vertical axes, both in natural and fractal images (Foulsham and Kingstone, 2010). Indeed, preliminary results of the present study confirmed that, depending on the image, saccades close to horizontal (0° or 180°) or vertical (90° or 270°) angles prevail. As a result, a good procedure to compare images is to consider the rate between horizontal (angle between 45° and −45° with respect to horizontal) and vertical (45° and −45° with respect to horizontal) saccades. For this purpose, a V-index (Vi) was defined, i.e. a verticalization index of saccades and drifts that expresses the rate between vertical and horizontal saccades. Its formula is $Vi= (W*NSV-H*NSH)/(W*NSV + H*NSV)$, H being the height of the screen in pixels, W its width, NHS is the total number of horizontal saccades, and NSV total number of vertical saccades. The formula was sized to the dimension of the screen, as stated by Lau et al. (2001); (further details in Supplementary Material).

Additionally, some other analysis techniques for visual images of material culture were included too, such as the density and the complexity of visual information by means of maps of visual saliency (Itti, 2007), and height-to-width aspect ratio (AR). These data were processed using MATLAB.

The study involved four different experiments and 99 participants in total (average age 34, age range 23–59) who carried out 124 different tests (25 people repeated Experiment 4 as part of the experimental strategy), as a result of which we finally had 117 valid tests.

In the first experiment (E1 in this paper, code Ex14061 –this code identifies the raw data of the experiment, available on the open access repository Digital. CSIC), a series of six pots was presented in two consecutive batches, the first by free viewing (FE) and the second by

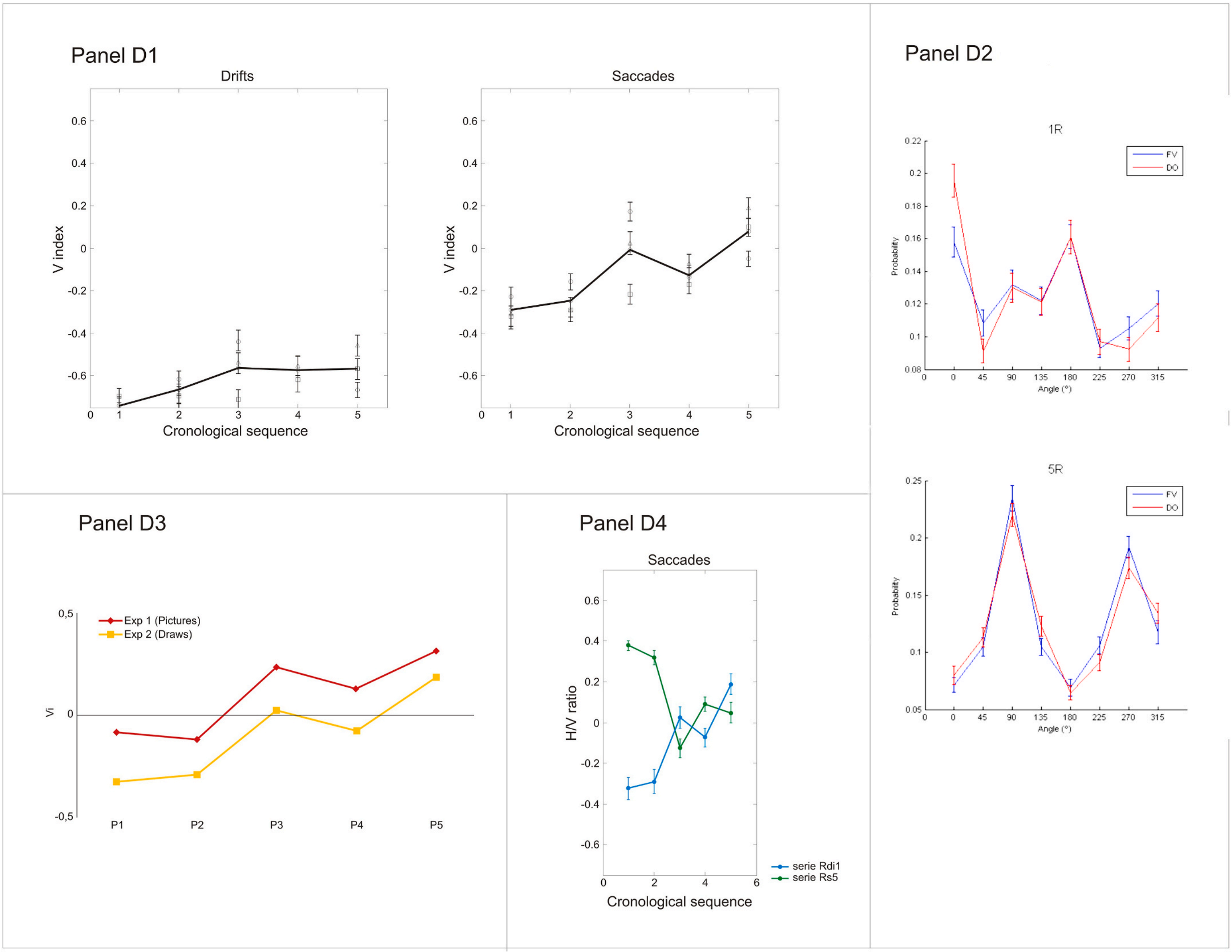

Fig. 5. Results confirm that Vertical Index (Vi) is closely related to the chronology. Panel D1 shows the Vi tested in E1 and E4; saccades display in both a stronger effect than drifts, as explained in the text. The way the pots are viewed does not change depending on the task; free viewing and directed observations gave substantially the same results in E1, as can be observed in the saccades angle (Panel D2). The comparison of Vi of Experiment E1 and E2 show that there are not significant differences between looking at photos or drawings of the same pots (Panel D3). Experiment E4 shows that eye movements generally follow the sense of the decoration even if we change the position of the pot, as demonstrated by Vi of original pots (series X.1) and Vi of series Rs5 (Panel D4).

directed observation (DO). For the directed observation the observer was asked questions about the pot before the image was presented. Of the six presented pots, five belonged to one of the different ceramic styles as described above, and one was a distractor. Each image was viewed for 30 s. The pieces were presented to each participant in a random order to prevent any bias in the results. In the second experiment (E2, code Ex14062), a series of black and white drawings of the same pots were presented in order to avoid the usual differences between images due to their distinct luminance (i.e. the amount of light emitted by an object or surface or, more precisely, a photometric measure of the luminous intensity per unit area of light travelling in a given direction). Such circumstances could affect the pattern of eye movements and especially the pupil response, as well as their saliency. In the third experiment (E3, Ex14071), photographs of the same pieces were shown, but this time replacing the front view with perspective views, making it possible to see the relief and shape of each piece more clearly, and changing the position of the decoration; (Fig. 3).

Finally, after first processing and interpreting the results of tests E1 to E3, we designed the fourth experiment (E4, code Ex14091), radically changing the observation conditions in order to maximise the results obtained in the previous experiments. The observation time was reduced to 15 s and a total of 40 images were presented, belonging to 8 different series (Fig. 4): one included the five pots of the previous experiments (the undecorated (distractor) pot was not used in this experiment); the other two included five new pots from the same periods. The aim of this was to confirm the visual response produced by ceramics from a specific period in E1-E3. Five further series were variations in the conditions in which the pots of the first series were presented, in order to verify to what extent the materiality of each decorative style determines the pattern of visual observation (as we had seen in E1, E2 and E3) under very different circumstances. Here the position of the decoration on pots was completely altered; the decorations and corresponding pot shapes were interchanged, or the decoration was eliminated from the body of the pot in order to see if the visual exploration pattern is influenced by the shape of the pot itself. The pots were even shown lying on their side, in order to test whether the sense of visual exploration of the pot and its decoration remained the same if the position of the pot was changed.

A total of 68 participants took part in E1, seven of whom had to be excluded from the analysis due to the failings of recordings. The sampling was gender balanced. The mean age of the remaining 61 participants was 36 (range of 15–58). The participants made up 5 different sample populations based on their degree of expertise in the experiment:

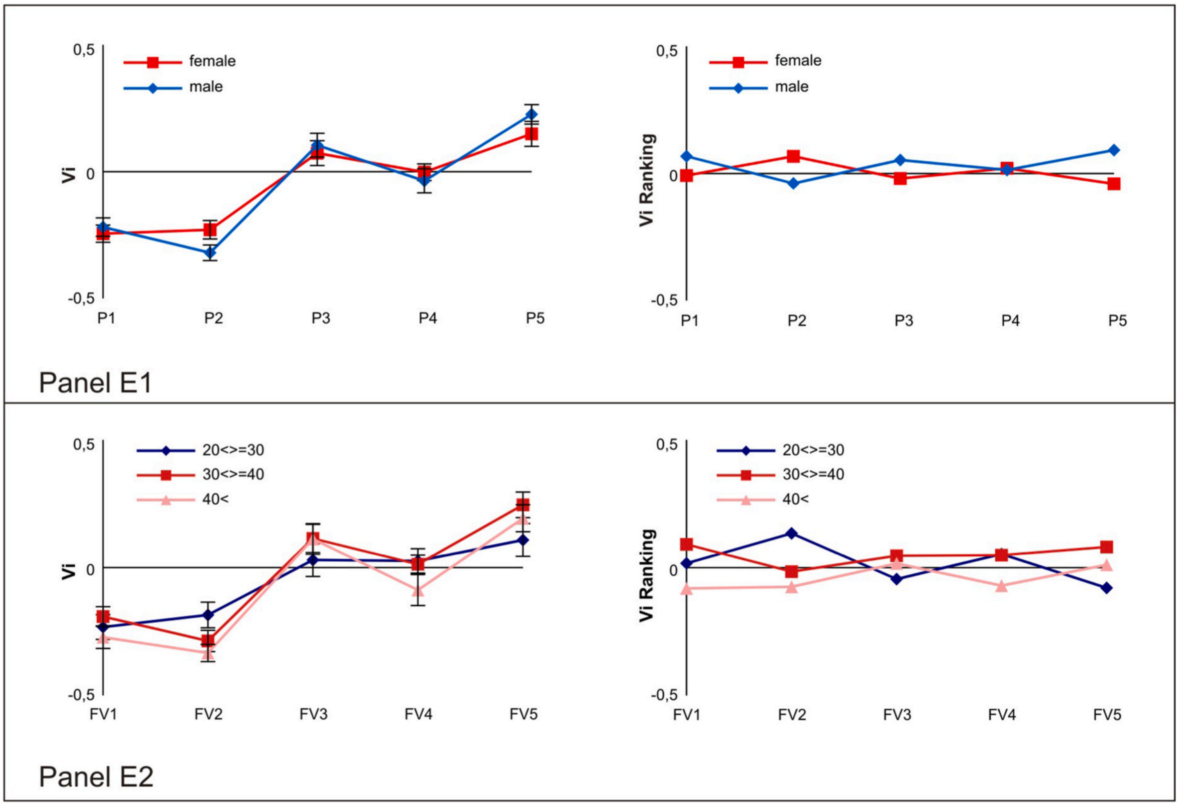

Fig. 6. Analysis of Vi in Experiment E1 did not find any relevant differences in terms of gender (Panel 5.1) or age (Panel 5.2).

a first group consisting of 13 people who had a high degree of specific knowledge and were aware of the working hypotheses, all of whom belong to the primary institution (INCIPIT-CSIC) for this research (mean age: 40); a second group of 12 people had a high degree of specific knowledge (archaeologists) since they knew the material, but they were not familiar with the working hypotheses (mean age: 34); a third group was comprised of 11 specialists in the production of ceramic items (mean age: 49); and finally a group consisting of 25 persons of the general public had no specific familiarity of the pottery or the working hypotheses (mean age: 30).

A total of 10 participants took part in E2 (mean age 32), and 10 participants in E3 (mean age: 37). Finally, in E4 a total of 36 people took part, 25 of whom had already taken part in the previous experiments (mean age: 34), though none of them were members of the INCIPIT and they were unaware of the project. It is important to add that any supposed effects of priming in this experiment are rejected as the volunteers were not required to provide any answers, nor were they guided in any way in this free viewing experiment. Therefore, in the absence of correctness or incorrectness in the way of looking, it is highly improbable that the pot they had assessed previously, would affect the pot in the subsequent experiment that was carried out months later. Moreover, the suggestion of such a strong alteration of the internal cognitive model, which as mentioned previously is studied over timespans of thousands and ten-thousands of years, is not deemed possible or relevant.

4. Results: different pottery styles provoke distinct visual behaviours

The analysis of E1 showed that the task (FE or DO) did not affect the visual exploration, as the outcomes were practically the same (Fig. 5.1), and implies that providing background information on the pots (DO) did not affect the ETA results. The results of E2, revealed that the visual reaction did not change substantially between observing photos or drawings (Fig. 5.2). We also confirmed that the visual behaviour test where the observers were exposed to images for 30'' was consistent with that recorded in the first 15''. Therefore, to avoid noise and simplify the experimental process, the time of observation can be reduced. This also allows the increase of the number of images presented. Next, E3 showed that the visual exploration of the image observed frontally or with a 3D effect was virtually the same (Fig. 5.3). Even though the eye movements do adapt to a change in the position of the pot, the results show that the volunteers were still looking at the same points and following the general trend of the decoration.

Altogether our analyses show a clear tendency of increasing Vi through chronological time for all experiments. No gender (Fig. 6.1) or age (Fig. 6.2) differences could be detected. Moreover, all sampling populations display similar Vi values. A minor exception is the "non-expert" group, which presents smoother fluctuations than the three "experts" groups (INCIPIT members, archaeologists and potters) (Fig. 7). This implies that the non-experts are less reactive to the materials (Appendix A Fig. 7). Experts' Vi shows a strong increment when observing the Bell-Beaker vessel (pot 3), whereas the non-experts' visual pattern is not as disruptive. This could realistically be ascribed to the experts' knowledge regarding the significant vertical differences in Bell-Beaker decoration, in contrast with the non-experts' probable assumption that the decoration adopts a repetitive pattern.

Further on, we estimated to what extent the visual behaviour for each pot could be determined by the general form of the pot and the range of its decorated belt. For this we analysed the aspect ratio of each pot, using the formula $AR = (V–H)/(H + V)$. Bronze Age and Iron Age pots (3, 4 and 5) display an AR (in form as much as in decoration) that is more vertical than Neolithic pots. The comparison between AR and Vi show that expert groups mainly focus their attention on the decoration, while the non-expert groups gaze the pot more freely and following its salience, either caused by the decoration or by the texture and colour of the pot (Appendix A Fig. 17).

To contrast these results, we analysed the visual exploration patterns of the pots during E4, where the original pots were artificially modified

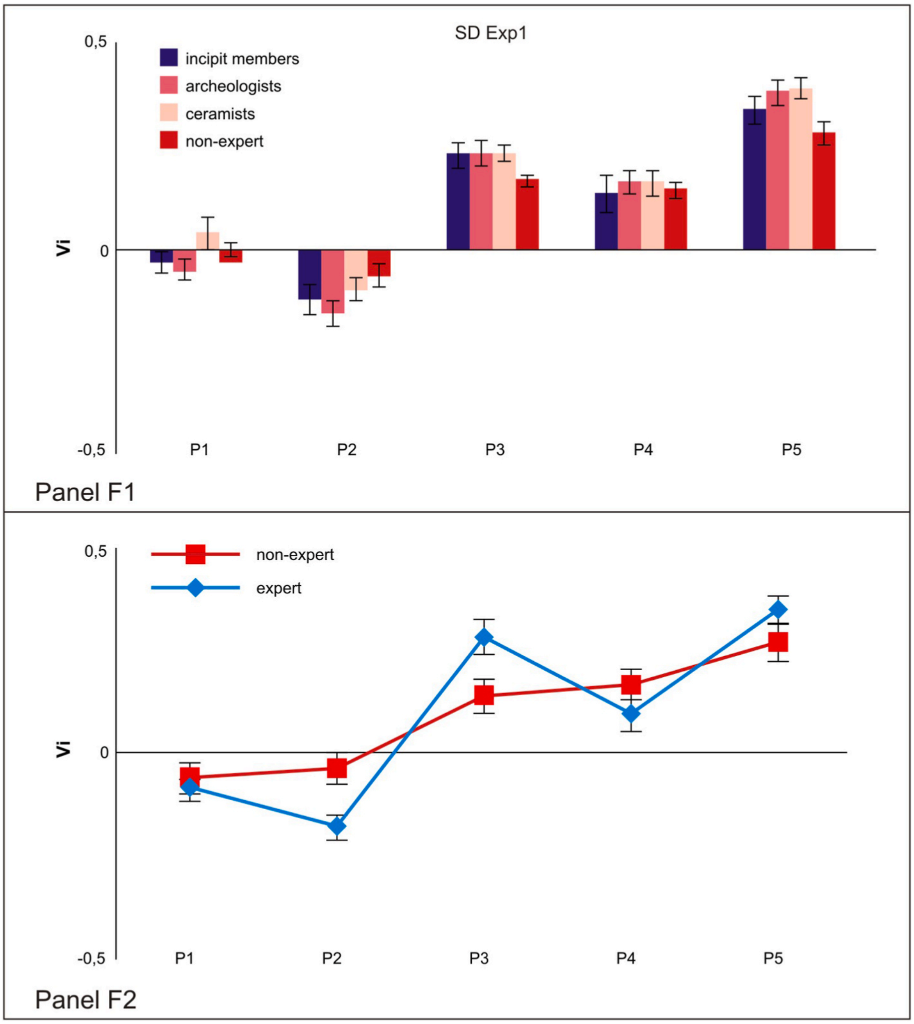

Fig. 7. Comparing the eye behaviour of the different expert groups in Experiment E1 allows to confirm that Vi does not change significantly depending on the knowledge of the material (Panel 6.1) and degree of expertise by observers. Comparing experts as a whole (archaeologists, potters and participants who had previous knowledge of this research) with non-experts (Panel 6.2), shows that the experts are more influenced by the orientation of the decoration than the non-experts, in the sense that their Vi is lower when looking a decoration that is highly horizontal (pot 2) and higher when looking a vertical decoration (pot 3).

(Fig. 4). The result of this experiment was that the decoration, supplemented by the form of the pot, imposed the visual response pattern of the observer. In other words, this confirmed that the material characteristics affect the visual behaviour. For instance, the comparison of the Vi of the undecorated and the decorated (original) series, shows that the presence of the decoration reinforces the Vi (Appendix A Fig. 10). That is, decoration enforces horizontal exploration in pots 1 and 2, and vertical exploration in pots 3, 4 and 5. The interchanging of forms and decorations (Appendix A Fig. 11) confirms the effect of the latter on the visual exploration of the pots. Thus, the application of Late Iron Age decoration (pot 5) on a Middle Neolithic pot (pot 1, whose AR and morphology present the most horizontal Vi pattern), transforms the Vi of said pot 1 in a vertical one. The same occurs when decoration of pot 4 (Middle Iron Age) is transferred to pot 2 (Late Neolithic). Respectively, the transference of the decoration of pot 1 (MN) to pot 3 (a bell beaker with a totally vertical Vi), horizontalizes this pot, and the same occurs when decoration 2 is incorporated in pot 5 (Late Iron Age). Meanwhile the transference of bell beaker decoration of pot 3 to pot 4 (MIA), reverts its Vi in the highest one. Finally, the Vi of the "lying down" series (Appendix A Fig. 15) show that a horizontal decoration is transformed in a vertical one when the pot is placed on its side, while the vertical decorations tend to become more horizontal.

5. Conclusions: from the order of human materiality to the human engagement with technology

Our primary observation is the unsurprising reassuring that the decorated regions are significantly more visited than the non-decorated regions, and that the decoration arranges and orientates the visual exploration (Fig. 8). Due to the novelty of this thematic, there are few reference studies which can be compared to. Some studies carried out for marketing purposes on the visual exploration of jam jars (Piqueras-Fiszman et al., 2013) indicate that the visual reaction when looking at them is mainly punctual, focusing on the items of relevant information that are given priority on each type of container (i.e. the photograph of the jam, or the original fruit, or the trademark). This is the basic principle of the studies of visual salience (Itti et al., 1998), mentioned earlier. What is remarkable though, is the observation that apart from this, the decoration of archaeological pots forces the gaze to shift towards exploring the body of the pot and comprehend it in the double sense of understanding and apprehending; (this was also stated by Tokitsu, 2004, but never considered in detail).

There are general consequences that arise from these results. Primarily, these indicate that through time there are significant changes in how visual perception operates. Our pots show a gradual transition from a visual behaviour in which firstly a simple horizontal gaze predominated, later shifting to a more robust horizontal-linear gaze and finally to a gradually vertical and finally hierarchized gaze. These ways of looking at material culture are compatible with the ways of gazing that are used in other human phenomena and codes, from architecture to the social landscape. Bradley's Idea of *Order* (2012), especially his emphasis on Neolithic circular arrangements, are supported in the light of these data; the same occurs with Ingold (2007) or other works (Criado-Boado, 2014; Criado-Boado and Vázquez, 2000, recently confirmed by Llobera,

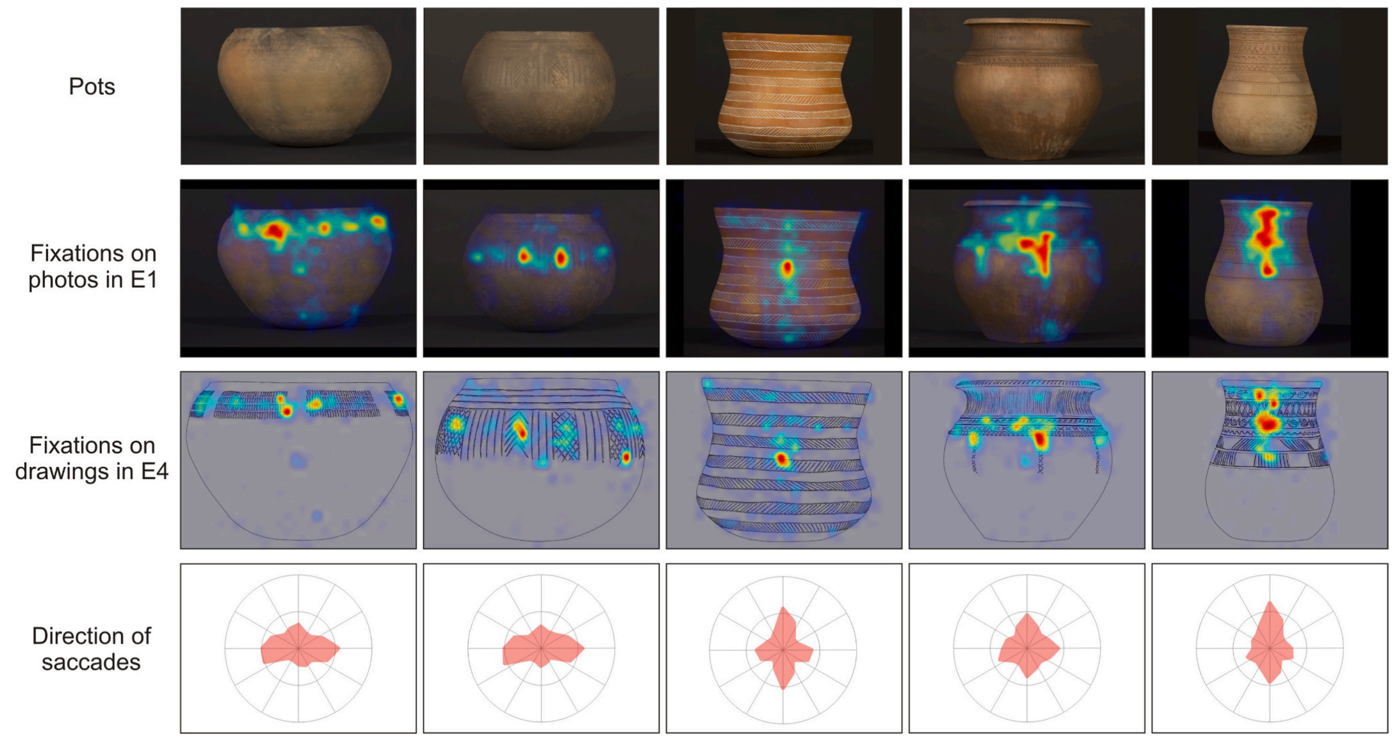

Fig. 8. Heat maps of aggregated fixations for all the experimental participants clearly show that gaze concentrates attention in those areas of the pot with more visual information, either on photos (from E1) or drawings (from E4). But it is even more important to realize that the dominant direction of the saccades (ie. how each pot is actually visually explored by observes) changes depending on the decorative style.

2015). These changes through material styles correlate with social complexity, and with the main features of each socio-cultural formation, in the sense that, whenever a society becomes more complex, a bigger verticalization of the visual patterns of its objects come into existence. According to our pots, horizontal visual exploration predominates in social formations with limited levels of complexity, while vertical exploration predominates in contexts marked by social complexity and ranking.

Leaving implications in terms of prehistoric sociology apart, this research points towards the agency of material culture and highlights new aspects that allow for a better understanding of its shape, role and meaning. A good example of this is Bell-Beaker pottery, which marks the transition between the Neolithic and Bronze Ages (Kristiansen, 2014, 2015; Kristiansen and Earle, 2015)). This “disruptive” character of the Bell Beaker is reinforced through perception studies showing that it marks the turning point from the fundamentally horizontal pattern of exploration for pots 1 and 2 towards the vertical pattern of pots 4 and 5. Although the Bell Beaker is clearly different from the latter, in which the upward and downward eye movements are balanced. The Bell-Beaker bowl (no. 3.2) is an excellent example of this effect, because, in spite of having a form with an AR that reinforces its horizontality (without decoration this form would be seen with a predominantly horizontal gaze), the incorporation of Bell-Beaker decorations forces a vertical visuality of the pot.

Though visual heatmaps of eye fixations (Fig. 8) are highly intuitive and simple ways to illustrate the differences between different objects in terms of visuality, their significance ends here. The main merit of this study has been to assess not what is observed, but rather *how* something is observed, what the visual behaviour is. It shows how a simple technique as the Vi enables the characterization of patterns of eye movements imposed by distinct styles of material culture. There is a lot more, beyond heatmaps.

6. Further discussion

Following these promising results, both in terms of shedding light on prehistoric sociology, expanding the horizons of materiality as well as establishing ETA as a valuable analytical tool in archaeological research, future research should aim for wider dimensions. To avoid the limitation of presentism, once the described methodology is established, multicultural cross-studies as well as multisensorial dimension of how perceptions are experienced should be taken into account. The understanding of perception is incomplete without considering the fact that our worldly experience is created through the body and shaped by our actions, combining our different senses and reflexes towards the exterior world. The idea of *action in perception* (Nöe, 2004; Mitchell, 2005) becomes the key for an enactive neuroscience of perception (Varela et al., 1991), which is not only devoted to measure the cognitive and body reactions to visual perception, but also in seeing how these interact with gestural exploration.

If we do adhere to the present we are allowed to highlight a different contribution of this study. A possible use can be also found in the approximation to how the agency of things operates *today*, and which perceptual mechanisms trigger interactions with archaeological heritage. This can then be used to guide our relationship with heritage. What we today call “heritage” is a function of the social value added to specific cultural objects, the result of a categorization made in the present day (Criado-Boado et al., 2015). Thus, an account of how heritage is perceived by the public is required to know its social values and capabilities. Our approach to the cognitive dimension of material culture could further the understanding of the subjective reactions produced when seeing heritage artefacts and images, when interacting with originals, replicas or reconstructions. In this way, the study of the visual perception of objects would provide many practical applications for analysing the present-day role of heritage in our societies and people relations to heritage assets, either objects, buildings or even cultural landscapes. This opens broader perspectives for, and new applications of, the study of material agency of objects through ETA.

Now, to detail a final possibility offered by this study, we briefly shift to the future. It has been calculated that by 2020 there were 100,000 million sensors throughout the whole world capturing information of all kinds and processing it digitally, connected together and therefore functioning as a vast, extended human brain (Rifkin, 2014). If this is the scenario that awaits us, then it is for the best that archaeological studies of material culture contribute to the building of an awareness of this reality. Other disciplines could also contribute to such understandings, but cognitive research on material culture can fold historic time to add to these matters. Robots and cyborgs will require this kind of research to learn how to behave (Constant et al., 2021). This can be feasibly sought from material culture and material images, which at the same time allow one to introduce the history and social dimension of the study of the visual process.

This research makes contributions of great importance to archaeology and other disciplines such as the social history of thought and visual cognition studies regarding the comprehension of material culture. The visual response of experimental participants provides meaningful insights on how the agency of material culture operates and how the mind is engaged with materiality. The approach we outlined avoids to hint that there is an imbalance between (subjective) theoretical reasoning and (objective) data interpretation. Altogether we foresee a short-term expansion of eye-tracking analysis of archaeological material culture thanks to the implications of this study. The techniques are already available, and they are neither costly nor complicated. They are capable of offering new insights into material culture studies, providing results that are of great importance for a wide range of fields, from the humanities and social sciences to the "hard" sciences. A new and promising line of research is opened, implementing ETA to characterize visual behaviour is a new archaeometric facility that can be used in archaeological science.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2023.105770.

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