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Cave acoustics in prehistory: Exploring the association of Palaeolithic visual motifs and acoustic response

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During the 1980 s, acoustic studies of Upper Palaeolithic imagery in French caves—using the technology then available—suggested a relationship between acoustic response and the location of visual motifs. This paper presents an investigation, using modern acoustic measurement techniques, into such relationships within the caves of La Garma, Las Chimeneas, La Pasiega, El Castillo, and Tito Bustillo in Northern Spain. It addresses methodological issues concerning acoustic measurement at enclosed archaeological sites and outlines a general framework for extraction of acoustic features that may be used to support archaeological hypotheses. The analysis explores possible associations between the position of visual motifs (which may be up to 40 000 yrs old) and localized acoustic responses. Results suggest that motifs, in general, and lines and dots, in particular, are statistically more likely to be found in places where reverberation is moderate and where the low frequency acoustic response has evidence of resonant behavior. The work presented suggests that an association of the location of Palaeolithic motifs with acoustic features is a statistically weak but tenable hypothesis, and that an appreciation of sound could have influenced behavior among Palaeolithic societies of this region.
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I. INTRODUCTION

Around 40 000 yrs ago, important cultural and artistic innovations appear among the early human societies of Western Europe. These include cave paintings (parietal art),

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the production of bone aerophones, and portable items of mobiliary art, including both human and animal figures and occasional theriomorphs (Clottes *et al.*, 1995; Conard *et al.*, 2009; Morley, 2013). Considerable evidence exists for the significance of organized sound in prehistory (Megaw, 1968; Scarre and Lawson, 2006; Till, 2009; Fazenda, 2013; Wyatt, 2009; Morley, 2013) and previous researchers have suggested links between painted caves and sound or music making (Reznikoff and Dauvois, 1988; Waller, 1993b).

The use of musical instruments by these early European societies indicates an appreciation of sonic aesthetics and acoustic ecology in what would have been an exclusively oral and aural culture, long before the adoption of writing systems. Our aim is to explore whether this appreciation of sound extended to the acoustic response of spaces, and how significant this was among Palaeolithic societies. This paper seeks evidence for a relationship between early visual motifs (Palaeolithic paintings and engravings on cave walls), particularly their positioning, and an appreciation of acoustic effects that originated from interactions of sound with physical features of the surrounding environment at those positions, termed in this paper the *acoustic response*. It provides a full description of methods, results, and conclusions.

Iégor Reznikoff and Michel Dauvois, both together and individually, have explored how Palaeolithic human-made motifs in caves might be related to acoustic response (Reznikoff and Dauvois, 1988; Dauvois, 1996, 1999, 2005; Reznikoff, 1995, 2002, 2006, 2011). Their research "shows a relationship between these paintings or signs, and the sounds that might have been produced adjacent to them" (Reznikoff, 2002: p. 3), at a series of French caves, including Le Portel, Niaux, Isturitz, and Arcy-sur-Cure.

Our research builds upon and develops this earlier work of Dauvois and Reznikoff and applies a systematic scientific approach to establish whether there is an association between the location of motifs in caves and the acoustic response at those locations. A set of five caves, each containing numerous motifs, are investigated in terms of the nature and location of the motifs and the acoustic response at those positions measured by state-of-the-art techniques and equipment. For comparative statistical analysis, a number of control positions where motifs are absent (or exceedingly rare) were also included in the analysis.

In the discussion of our results, we have used terms such as *likely*, *explanatory*, and *association*, strictly in a statistical rather than an interpretative sense. Also, the term *motif* is employed here for a number of reasons: "art" is a problematic and potentially anachronistic term carrying numerous post-prehistoric implications; "painting" is inaccurate as it does not extend to sculptures or engravings. Furthermore, the motifs are highly variable, from simple dots or lines, to subtle exaggerations of natural rock shapes, to the well-known but much less numerous illustrations of animals. "Motif" is a term that covers all examples.

This paper presents relevant research context in existing publications (Sec. II), the archaeological setting of the caves studied (Sec. III), details of acoustic measurement and the acoustic responses obtained (Sec. IV), statistical analysis (Sec. V), and a discussion and interpretation of the results (Sec. VI), before concluding remarks.

II. RESEARCH CONTEXT

In his study of the French caves, Reznikoff explored a number of research questions. Are there "more paintings or signs in locations with the best resonance or sound quality" (Reznikoff, 2002: p. 39)? "To what extent would it be possible to establish on this factual and experimental evidence the use these people made of sound and voice in relation with the paintings or other signs in caves? (…) Is there a link between the location of a painting or a sign and the sound value of this location in the cave?" (Reznikoff, 2002: p. 40). Reznikoff explored the "resonance of sounds" in terms of their intensity and duration, and also considered the number of echoes present. Intensity in this case referred to amplitude, or volume. Duration expressed how a sound is sustained, and is perhaps best thought of as reverberation time (RT), although echoes complicate such a definition. A sound level meter was used to measure intensity, and a wristwatch, or counting off seconds aloud, was used to calculate duration. Excitation of these acoustic effects was effected through vocalizations or the generation of noise signals.

Developed in the 1980 s, the methodology employed by Reznikoff in these studies presents a number of difficulties. The Palaeolithic populations that inhabited and decorated the caves were Anatomically Modern Humans, with vocalization capacities similar to our own. Repeated vocalizations by a human performer will never be sufficiently standardised to provide a repeatable test source, however, since even slight differences between successive vocalizations might excite different acoustic responses. In addition, the experimenter is prone to introduce bias when using his or her own vocalizations to identify particular points with interesting acoustics. Furthermore, the voice only covers a limited frequency range that varies widely between individuals, from low basses to high sopranos. The use of counting or a watch to measure reverberation is, by contemporary standards, also inadequate. An individual's assessment of when reverberation has ceased, perhaps expressed to the nearest second, is, by its very nature, subjective, and the measured RT becomes dependent on: the loudness of each individual vocal sound, the background noise, and the hearing acuity of the listener.

Dauvois (1999, 2005) used continuous noise signals in the range 25 to 300 Hz (Dauvois, 1996: p. 24) to carry out similar tests. The approach is more repeatable, but his methodology lacks a detailed description in the available publications. Details of source and receiver positions, sound source type, or capture methods are not provided. The limited frequency range of the source signal suggests that Dauvois was interested in the low frequency response of the space, and the use of steady-state noise as an excitation signal means that measures of reverberation or echo were not directly possible. Nonetheless, based on his experimentation, Dauvois (1996) reports that, "it is the particular natural morphology of the cave that provides the resonance". The choice of source placement, "also took account of the sonority, a combination of sound, site and figure, but this is not systematic.

Elsewhere there is a significant co-incidence between signs and resonance (…) there is a Paleolithic definition of an acoustic space" (Dauvois, 1996: p. 25).

Although Dauvois suggests that the relationship between motif and sound is occasional rather than systematic, he postulates a strong relationship, but only provides circumstantial evidence to support his claims. He shows that acoustic results vary in positions where paintings are present, but there is no way to establish whether the two are related; whether, for example, acoustics might vary in a similar fashion in positions where there are no motifs. Neither results nor methodology were published in detail.

Reznikoff suggests that, "the Palaeolithic people progressed in the cave by using the voice and resonance's response as a sonar" (Reznikoff, 2002: p. 42). He defines resonance as "strong" where the average intensity of sound increases by more than 10 dB, or where resonance lasts for more than 3 s. "Most pictures are located in, or in immediate vicinity to, resonant places (…) Most ideal resonance places are locations for pictures (there is a picture in the nearest suitable place). Among the ideal resonant places, the best are always decorated, or at least marked." His search was for the "relationship between the location of the drawings and positions where resonance was present" (Reznikoff, 2002: p. 43). According to Reznikoff (2002: p. 49), "the location for a rock painting was chosen to a large extent because of its sound value".

In a later publication, Reznikoff (Reznikoff, 2006: p. 79) recognizes the importance of statistical analysis in demonstrating these relationships, stating that,

"a meaningful connection between man-made signs and the resonance of a cave (or of an open space in connection with rock-art), can, in my view, be established only on a statistical basis. Only such a systematic study is reliable: if among signs and pictures some are found to correspond to resonant locations, then we can assert this relationship as shown, if the positive connections are statistically significant. Otherwise doubt remains: perhaps the connection appears just by coincidence. For a statistical study to be effective, it must be based first for (i.e., on) a given cave (or space) and then, by collecting several such studies, one might begin a general comparative study."

Reznikoff estimates the correlation of "pictures found in well resonating locations," at 80% in Le Portel and Arcy-sur-Cure and 90% at Niaux (Reznikoff, 2006: p. 79). He acknowledges that in Niaux almost all the paintings are in the Salon Noir, where the whole chamber has very rich acoustics (i.e., long RT). Thus all the paintings in the Salon Noir are associated with similar acoustics. These percentages are clearly approximations and are not intended as a scientific statistical analysis. Reznikoff makes clear the need for a more detailed statistical study.

In the same publication Reznikoff suggests that, "red dots or marks are related closely to the resonance of the part of the cave where they are located" (Reznikoff, 2006: p. 79). The reference here is to amplitude, rather than (for example) to reverberation. Reznikoff also asserts that, "as a general rule, niches or recesses that are painted (with red dots, some marks or pictures) resonate strongly" (Reznikoff, 2006: p. 80). Indeed elsewhere he discusses red dots as being the most closely associated with sound.

In a separate series of studies, Waller (1993a, 2006) explores the relationships between rock art more generally (in open spaces as well as in caves) and sound. He suggests, "an acoustical motivation for the content and context of at least some rock art" (Waller, 1993b: p. 91). In Palaeolithic caves, Waller proposes that, for example, images of hooved animals may be placed in positions where echoes are present, to reflect the sounds made by the animal represented. He also argues that rock art is generally linked to sound, quoting numerous examples of rock art sites with unusual acoustics, as well as ethnographic and historical traditions indicating mythical or ritual relationships between rock art and sound, reverberation and echo. The methods used to test these relationships, employing cassette tape and simple impulse sounds such as the voice as a source, are again rather simplistic by today's standards and, while suggestive, do not provide any level of certainty.

Following on from research by Dauvois, Reznikoff, and Waller, the study presented here defines a methodology that looks for association between cave art and acoustic response within five caves in the Asturian and Cantabrian regions of Northern Spain. Both regions share the same sequence and approximate chronology of successive Upper Palaeolithic phases, from Aurignacian [42 000–35 000 Before Present (BP)], through Gravettian (35 000–25 000 BP) and Solutrean (25 000–20 000 BP) to Magdalenian (20 000–15 000 BP) (Zilhão, 2014: p. 1736). The caves involved are part of the Cave of Altamira and Paleolithic Cave Art of Northern Spain World Heritage Site (UNESCO 2: Ontañón *et al.*, 2008). The study focuses on four Cantabrian caves: La Garma, El Castillo, La Pasiega, and Las Chimeneas; and one Asturian cave, Tito Bustillo.

We explore a number of research questions. Can a statistical association be scientifically established between Palaeolithic visual motifs in caves and acoustics? What is the nature of the relationship between the two, if any? Are specific types of motifs (such as red dots) correlated with acoustic response? More generally, what can an acoustic study tell us about the archaeology of these caves, and the way they may have been perceived and experienced by prehistoric populations? In order to answer these questions, specific archaeological information was needed, notably an understanding of the typology and chronology of motif creation.

III. ARCHAEOLOGICAL DETAILS OF THE CAVES

A. Cave morphology and setting

The material culture found in the caves included in this study corresponds to the same cultural horizons as that in the French caves studied by Dauvois and Reznikoff. At the same time it must be recognized that the internal morphology and structure of the caves has undergone processes of modification (both human and natural) that inevitably affect their acoustics. Some areas of these caves may hence exhibit acoustic responses that have changed since prehistory. The five caves were selected to provide a range of alteration from slight (La Garma) to significant (Tito Bustillo, El Castillo). The largest, most dramatic caves (Tito Bustillo and El Castillo), are the most changed, following 20th century alterations to make them accessible to the visiting public.

The morphology of these caves is intricate, composed of galleries that branch off into other galleries or smaller side chambers, through narrow passages. As a result, the architectural effects of each gallery or section are typically acoustically decoupled from those adjacent to it. Plans of the caves can be found in the project archive (https://tinyurl.com/n5pmm8m).

The most significant naturally occurring change to the architecture of the caves came about through the closing or sealing of their original entrances by rock-falls or by sediment accumulation. All of the locations chosen for acoustic measurements included in the analysis are a sufficient distance away from the original or modern entrances for that to have little effect. Some of the measurements were taken in places where the morphology of the cave is altered (for example through modern lowering or levelling of cave floors or the provision of a modern staircase) although most were taken in spaces where the archaeologists believe the original morphology is preserved, particularly in difficult-to-access side chambers. Although exceptions to this were observed in very few side chambers, none of these would have recorded a different acoustic response had the original entrance been open at the time of our measurements. Where possible, the positions of the microphone and sound source were selected to avoid direct influence from modern modifications to the cave morphology.

B. Chronology

The chronology of Upper Palaeolithic parietal art has long been a subject of debate. Early attempts at establishing a chronology were based on the assumption of a unilinear stylistic progression (Breuil, 1952; Leroi-Gourhan, 1965). From the 1990 s, however, the application of scientific dating techniques, particularly accelerator mass spectrometry radiocarbon and uranium series dating (e.g., Clottes *et al.*, 1995; García-Diez *et al.*, 2013; Pike *et al.*, 2012; Valladas *et al.*, 2001; Valladas *et al.*, 2005) have challenged these earlier schemes. While the validity of the dates and the methods that underpin them have met with varying degrees of criticism, it is undeniable that we can no longer treat the chronological arrangement of Upper Palaeolithic art as a simple progression from rudimentary to complex forms.

Despite these advances an overarching chronology for parietal art has yet to be realized. Although scientific techniques provide a somewhat clearer picture, only a limited amount of Upper Palaeolithic cave art has been reliably dated. Given the sparse radiometric dating of the motifs within the caves included in our study, we have taken a heuristic approach to the interpretation of their chronology, categorizing them into three phases: early (Aurignacian/Gravettian c. 42 000–25 000 BP), middle (Solutrean 25 000–20 000 BP), and late (Magdalenian 20 000–15 000 BP). This incorporates stylistic considerations alongside recorded absolute dates (where available).

The earliest motifs appear to be dots, discs, and lines (Pike *et al.*, 2012), followed by hand stencils, usually in red (Pettitt *et al.*, 2014). These we attribute to our "early" phase. Animals, mainly in outline, and geometrics such as tectiforms constitute our "'middle'" phase, whereas the elaborate and sometimes polychrome figures of the Magdalenian period, well represented at caves such as Altamira, are coded as "late." This chronology is supported by studies seeking to reconcile stylistic and radiometric dating (e.g., Alcolea González and de Balbín Behrmann, 2007).

Chronology is important when addressing cave acoustics for several reasons. First, given the cumulative and potentially shifting distribution of motifs within these caves, it is probable (and in some cases it is documented) that the earliest motifs in a given cave were located in specific places, or limited to one section or gallery. Later motifs may not only have filled out this pattern but may also have extended to new areas. Hence any attempt to relate cave acoustics to the distribution of motifs that did not control for chronology would risk conflating a series of potentially distinct patterns. There may have been a close association between the location of motifs and acoustic signals in some phases, but not necessarily in all phases of cave art.

Second, the likelihood that behaviors associated with the motifs changed over time make chronology especially important. Cave acoustics may have been significant for certain kinds of behaviors in certain periods, but not necessarily in the same way throughout the entirety of the long period (over 30 000 yrs) during which motifs were being painted or engraved in these caves. The contention that behaviors will have changed through time makes controlling for chronology, albeit inexactly, essential in a statistical assessment of the relationship between acoustics and the placement of motifs.

The coding of motifs in the individual segments of these caves that were targeted in this study is summarized in Table I. It should be noted that, as a control, measurements were taken in a number of sections without (or with minimal) recorded Palaeolithic motifs [La Garma section 7; La Pasiega Gallery A (outer); and Tito Bustillo side chambers TB1 and TB2].

IV. ACOUSTIC MEASUREMENT AND RESPONSE

A. Acoustic measurement

In order to explore potential associations between visual motifs and acoustics, information on both had to be collected systematically and collected in a manner that allowed for statistical analysis. Relevant literature on the caves was explored in order to contextualize the research archaeologically (Arias *et al.*, 2001; de Balbín Behrmann, 1989; Berenguer Alonso, 1985; Breuil *et al.*, 1913; Cabrera Valdès, 1984; González Echegaray, 1974; González Sainz *et al.*, 2003). Professor Roberto Ontañón of the University of Cantabria and director of the Cantabria Prehistory and Archaeology Museum, who had archaeological oversight of many of the caves, and Professor Manuel Rojo Guerra of the University of Valladolid, both took part in the field work advising on archaeological matters.

TABLE I. Chronology of cave sections. Sections of the five caves have been assigned to three phases based on the style and inferred age of the motifs that are present: "Early" = Aurignacian and Gravettian c.42 000–25 000 BP; "Middle" = Solutrean c. 25 000–20 000 BP; "Late" = Magdalenian c. 20 000–15 000 BP. For the locations of the cave sections see plans in https://tinyurl.com/n5pmm8m.

Cave	Section	Early	Middle	Late
El Castillo	Panel de las Manos	■	▒	
El Castillo	Sala del Bisonte			■
Las Chimeneas	Main chamber			■
Las Chimeneas	Deer chamber			■
La Garma	Section 1			
La Garma	Section 6	■		
La Garma	Section 7			
La Garma	Section 9	■		
La Pasiega	Gallery A (outer)			
La Pasiega	Gallery A		■	
Tito Bustillo	El Conjunto de la Ballena			■
Tito Bustillo	El Carmarín de las Vulvas	■		
Tito Bustillo	Galería Larga			
Tito Bustillo	Galería de los Caballos			■
Tito Bustillo	El Conjunto de los Signos Grabados		■	
Tito Bustillo	Side chamber TB1			
Tito Bustillo	Side chamber TB2			
Tito Bustillo	Galería de los Antropomorfos	■		

Our methodology was to capture the impulse response by acoustic measurements at a number of specific positions in a cave, and to record information about the archaeological context at each position. A range of data was recorded at each measurement point, including the specific position and type of source (loudspeaker) and receiver (microphones) within the cave, and their distance from motifs (where the latter were present); the presence or absence of a motif or motifs; the type of motif(s) (painting, engraving, rock sculpture, dot, disk, line, sign, horse, bison, bovid, reindeer, ibex, bear, bird, whale, fish, cetacean, anthropomorph, hand stencil); how many of each type were present; colors (for painted motifs); distance to the cave's original entrance; chronological information (phase); reference number of the audio file created; and reference codes for photographs taken at each position. The data were recorded in standardised field notes and plans, and all information was later collated in a spreadsheet.

Every acoustic measurement can hence be traced to specific source and receiver positions within the caves. Acoustic measurements were taken according to guidelines in ISO 3382 (2009) although a number of adaptations had to be implemented to accommodate the added difficulty of measuring within a cave environment. Source positions were chosen toward the centre of each cave section (chamber or gallery) that was being measured, always maintaining a sufficient distance from microphones to avoid source near-field effects. For each section, data for at least one source position and three microphone positions were collected. ISO 3382 (2009) recommends two source positions, and this was followed where possible and relevant. Some of the spaces measured were small (c. 25 m^3) rendering more than three measurement positions redundant. In addition, the uneven ground surface made it difficult to position source and microphone stands firmly in more than a few positions. In other cases positions were restricted because equipment could not be placed on fragile archaeological material. These and similar factors place constraints on acoustic measurements in archaeological sites such as these caves and differentiate them from the typical architectural acoustics measurements represented by ISO standards. These standards typically have a different purpose to the forensic examinations of the type required within this project; for example, the multiple source and receiver positions recommended in ISO 3382 (2009) are intended to obtain an average of the acoustic response to represent the diffuse field reverberation, whereas we were interested additionally in the variety of response.

Where motifs were present, measurement positions were selected by placing a microphone in front of them at a distance of 1 m from the motif. In some cases this was impossible to achieve, but in general the principle was followed. Control measurements, where no motifs were present, followed the same procedure, the microphone being positioned about 1 m from selected surfaces with no motifs.

To collect impulse responses, the sine sweep measurement method was used (Müller and Massarani, 2001). A logarithmic sine sweep, in digital format, sampled at 48 kHz, 16 bits, was generated within the range 20 Hz to 20 kHz with duration of 15 s. These settings, rather than higher sample-rates or bit-depths, were considered appropriate as they provide signal-to-noise ratios (SNRs) above 60 dB, which is sufficient for extraction of acoustic metrics, such as T30, from the impulse response. The restrictions on SNR in these situations are defined by the electroacoustic transducers and the environmental conditions rather than the recording equipment. The main measurement system employed a laptop and professional soundcard (Focusrite Saffire Pro 26 i/o, Focusrite Audio Engineering Ltd., UK). The sound source was a battery powered Bang & Olufsen Beolit 12 (Bang and Olufsen, Denmark) amplified loudspeaker, and the signal was fed to the speaker from the soundcard via a cable. The microphone signal was acquired via the soundcard and EASERA (www.easera.afmg.eu) measurement software was used to run the measurement and obtain the impulse response.

The Bang & Olufsen Beolit 12 speaker was chosen for a number of reasons. It has a reasonably flat frequency response, an acceptably wide polar pattern, and sufficient acoustic power; its small size and battery autonomy enables measurements without a power supply for several hours. The frequency and directivity response of the speaker measured in a fully anechoic room can be accessed via the online project repository in https://tinyurl.com/k7pxt95. Further specifications provided by the manufacturer can be found in https://tinyurl.com/n2ckb8j.

The performance of our measurement system was compared against a RT measurement taken in the large reverberation room at the University of Salford (7.4 m long × ~6.6 m wide × 4.5 m high) which has been designed with hard surfaces and non-parallel walls to give long empty room RTs with uniform decays. The room has the shape of a truncated wedge and has 11 plywood panels, each panel 1.22 m × 2.44 m, hung in the room to improve diffusion of the sound field. The measurements in this facility follow Clause 6.2.1.1 in BS EN ISO 354 (2003) with an excitation signal comprised of wideband random noise played into the room via a loudspeaker system mounted in a cabinet facing a corner. The sound is monitored at six positions with Brüel & Kjær type 4166 [Brüel & Kjær Sound & Vibration Measurement A/S (HQ), Denmark] random incidence condenser microphones. Our measurement system was then benchmarked using the same source and microphone positions, replacing the original source with the Bang & Olufsen Beolit 12 amplified loudspeaker and using the logarithmic sine sweep signal defined above to excite the room. Each of the microphone signals were then deconvolved in a post-processing stage as described in Müller and Massarani (2001) to obtain the impulse responses from which the benchmark values of T30 were determined. To extract T30, we follow the procedure originally proposed by Schroeder (1965), which is based on the backward integration of the energy contained in the impulse response. This results in a curve that represents the decay of energy from the arrival of direct sound through to the last reflections from the surrounding boundaries. From this curve, the T30 values are extrapolated by means of linear regression between the -5 and -35 dB values, obtained at each octave band after appropriate filtering. Table II shows T30 obtained when testing our system in the reverberant chamber. When compared to the reference measurements of the chamber, minimum and maximum errors of 0.01 and 0.2 s, respectively, were observed.

The measurement system and, in particular the excitation source, differs from the typical omnidirectional source prescribed in ISO 3382 (2009) for standard measurements, or systems employing studio reference loudspeakers, often with a matched sub-woofer to enhance the bass response such as in the work of Murphy (2006). These systems are, however, often large and heavy, which makes them impractical in a cave environment. A more portable configuration was thus devised to obtain responses in the most difficult to access spaces or where main power could not be delivered. This comprised the same Bang & Olufsen Beolit 12 sound source being driven with a pre-generated sine sweep, identical to that used in the main measurement system. The signal, sampled at the same sample rate and bit depth, was played on a handheld portable player connected directly to the sound source. The signal from the microphone was recorded directly onto a professional standard portable digital recorder (Sound Devices 744 T, Sound Devices, LLC, Reedsburg, WI) at a 48 kHz sample rate and 16 bit depth. The recorded sine sweeps were converted to room impulse responses as described in Müller and Massarani (2001). In both configurations of the measurement system, the same microphones (omnidirectional DPA 4006 microphones with B&K diaphragms) were used.

TABLE II. T30, in seconds, measured in a reverberant chamber for Bang and Olufsen Beolit 12 and the facility's RT measurement sound source.

Frequency	100 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	Avg error
REF	4.50	4.20	4.65	4.27	3.58	2.18	
Beolit 12	4.51	4.00	4.60	4.20	3.40	2.21	
Error	0.01	0.20	0.05	0.07	0.18	0.03	0.09

B. Acoustic responses

It is likely that both speech and music were part of the cultures that used the caves, given that speech evolved earlier (Fitch, 2010) and examples of musical instruments in the human cultures under study here have been reported in archaeological studies (Conard *et al.*, 2009; Buisson, 1990; García Benito *et al.*, 2016; Ibáñez *et al.*, 2015). Therefore it is appropriate to analyze the responses using a mixture of metrics that have been shown to relate well to a subjective response in room acoustics for music and speech. Although these metrics have been derived for and are widely used in performance spaces, they have also been commonly employed in the characterization of a multitude of human environments from churches (Magrini and Ricciardi, 2002) to soundscapes (Rychtáriková and Vermeir, 2013), including spaces both big and small (Stephenson, 2012; Vanderkooy, 2007). They represent common metrics that describe acoustic response in enclosed spaces and are thus useful for general interpretation of the data collected. Their interpretation is intuitive allowing an objective quantification of the responses measured using well established and perceptually relevant metrics which may be understood by all and, as we will demonstrate in Sec. V, useful in establishing and interpreting one of the principal dimensions of variance in the data collected.

From the measured impulse responses, 23 acoustic metrics were extracted, following well known methods reported in ISO 3382 (2009), Barron (2009), Kuttruff (2009), Steeneken and Houtgast (1980), Stephenson (2012), and Dietsch and Kraak (1986). These metrics comprise:

- T30 and early decay time (EDT) each extracted across six octave bands between 125 and 4000 Hz. The extraction of T30 values is as described above in Sec. IV A. The extraction of EDT follows the same method of Schroeder's backwards integration of the impulse response as that for T30 but the linear regression is obtained between the 0 and -10 dB points on the decay curve. Average values for T30 and EDT are obtained from the values at 500 Hz and 1 kHz octave bands as defined in ISO 3382 (2009). T30 and EDT are common acoustic metrics used to describe the acoustic response of spaces. While T30 pertains to the decay of acoustic energy homogeneously within a space and is related to the physical properties of the space (volume and surface area), EDT is perceptually more relevant to the sensation of reverberance and sensitive to the effects of early reflections (ISO 3382, 2009; Barron, 2009; Kuttruff, 2009).
- D50 and C80 each determined as a mean of the values obtained at 500, 1000, and 2000 Hz octave bands (Barron, 2009). D50 and C80 are temporal metrics of balance between early and late arriving energy, calculated for a 50 or 80 ms early time of arrival limit, depending on whether speech or music are the subject of analysis. C50 is directly correlated to D50 and has therefore not been used in this study.
- Speech Transmission Index is a metric describing the quality of the speech signal in terms of the loss of speech

modulation caused by reverberation (Steeneken and Houtgast, 1980).

- LFRT60diffs, LFRT60thr, LFdevflat, and LFdevsmooth are four figures of merit derived to quantify the quality of low frequency response of small rooms. Each of these figures of merit calculates a score between zero and one, where one corresponds to a response free of the particular low frequency artefacts it has been designed to identify. The frequency band within 32 and 250 Hz has been analyzed in third octave bands. LFRT60diffs determines absolute differences in T30 values between adjacent third octave bands, revealing a modal sound field when those differences are large; LFRT60thr reports on the degree to which the measured response in each third octave band is above the perceptual modal thresholds identified in Fazenda *et al.* (2015); LFdevflat calculates the deviation from the measured magnitude spectra to a flat magnitude spectra, and LFdevsmooth does the same to a smoothed version (third order polynomial fitting) of the measured response [see Stephenson (2012) and citations therein for more detail on these figures of merit].
- Echo criteria has been used for the detection of audible echoes in both speech and music signals (Dietsch and Kraak, 1986).

A general analysis of the acoustic response within the caves is now presented, including the measured T30 averaged for each section in each cave (Figs. 1–5).

In terms of T30, the acoustic response generally follows a common tendency in architectural acoustics, showing higher levels of reverberation at low frequencies and a decrease toward the higher frequencies. The values for reverberation are typically under 2 s, except in the large central gallery of Tito Bustillo, and in a large section near the entrance of La Pasiega and, even here, only at low frequencies.

It might appear surprising that we did not find a high RT (>3 s) in these caves. Indeed, we encountered a range of acoustic conditions, from small, very dry spaces, with reverberation (T30) below 0.4 s, to large spaces with T30 above 2.5 s at 500 Hz and below.

The rock faces within these caves were varied and their particular geology and morphology, i.e., the shape and surface conditions, do not, in general, support very long RTs. Although sections of La Pasiega featured smooth rock faces,

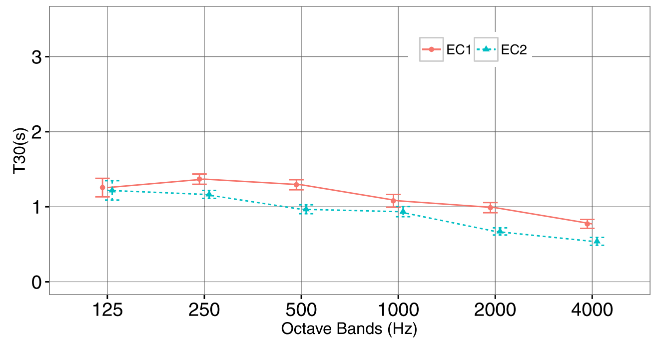

FIG. 2. (Color online) T30 for El Castillo. Means and 95% confidence intervals are presented for measurements in two different sections within the cave.

many other areas of the cave walls were characterized by much rougher surfaces, as for example throughout La Garma. Soft or porous rock can be worn into irregular shapes, and granular geology forms rough textures. The reason why very long RTs are not found in some caves might be due to the fact [as suggested by Cox (2014)] that the many passage-ways to adjacent cave sections, together with the diffusion produced by irregular or rough surfaces, force large amounts of wave-surface interaction, which has the effect of reducing the energy quickly.

La Garma section 7, where motifs are very rare, has a longer reverberation than the other three sections measured in this cave, where many more motifs are present. Section 6, where large numbers of dots and some hand stencils are present, appears to have a long reverberation at very low frequencies. Interestingly, in this section, the measured responses also suggest the existence of low frequency resonances reported by the low frequency metrics. Namely, the scores for LFdevflat are an order of magnitude smaller than at other positions in the cave, suggesting these positions might be associated with modal behavior (i.e., a specific frequency or frequencies which exhibit a long temporal decay and a marked amplitude level). This is also the case for the other low frequency figures of merit although the effect is not as marked. In the large cave of El Castillo, two areas were measured: a large open area (EC1, the "vertical bison" section) and a smaller contained space with a lower ceiling (EC2, the "hands panel"). Both sections appear to sustain a similar response, although the "vertical bison" section

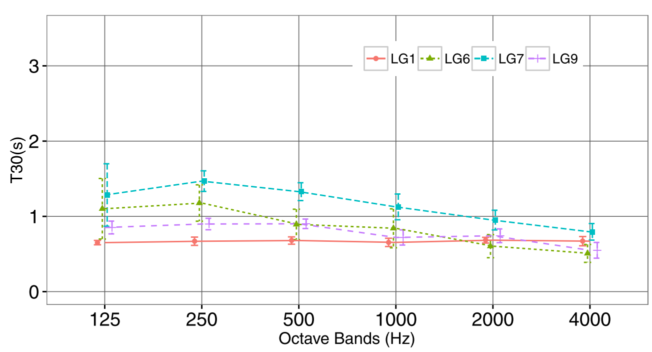

FIG. 1. (Color online) T30 for La Garma. Means and 95% confidence intervals are presented for measurements in four different sections within the cave.

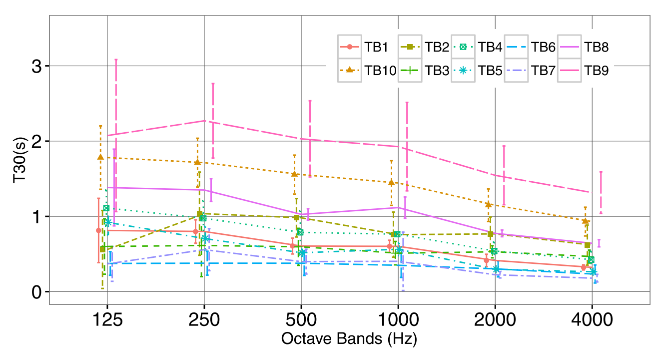

FIG. 3. (Color online) T30 for Tito Bustillo. Means and 95% confidence intervals are presented for measurements in ten different sections within the cave.

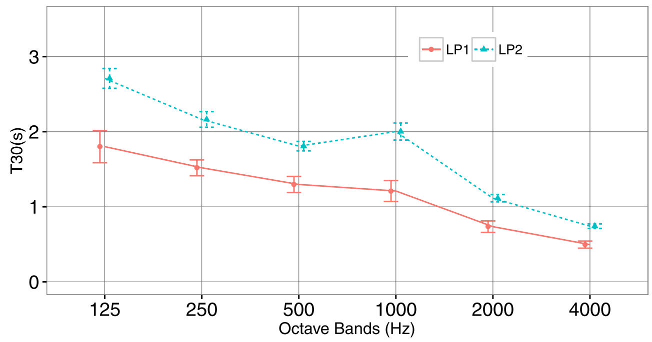

FIG. 4. (Color online) T30 for La Pasiega. Means and 95% confidence intervals are presented for measurements in two different sections within the cave.

understandably sustains longer RTs given it is larger and has a higher ceiling. The hands panel is directly adjacent to a large section with a high ceiling, and acoustic coupling between the two may account for the similarities in response. In Tito Bustillo, a number of small side chambers, of similar size and volume, were measured. These small chambers have similar RTs. The Chamber of the Anthropomorphs (TB8 in Fig. 3), extremely difficult to access and connected to the main gallery via a sequence of narrow passages at various heights, is larger than the other side chambers that were measured and sustains a longer RT. Longer RTs are also observed in the main central gallery of this cave, off which the side chambers open.

La Pasiega differed from the other caves in consisting of a network of long narrow passages. It has long RTs at low frequencies as a result of its tunnel-like shape (Kang, 2002). This can be clearly seen in the steep increase of RT values toward the lower frequencies. The corridor where most motifs are found (LP1 in Fig. 4) has lower values of T30 than the area near the modern entrance, where motifs are absent (LP2). All measured sections at Las Chimeneas seem to have a similar response, with no clear differences between sections, apart from the 1000 Hz values.

In general, the trends observed for RT (T30) across the caves are matched by other acoustic metrics derived from the impulse responses, such as EDT.

Figure 6 shows median and interquartiles for average T30 values obtained within each of the sections for each cave. The ISO 3382 (2009) standard defines single figure values for T30 and EDT, utilising the average of values

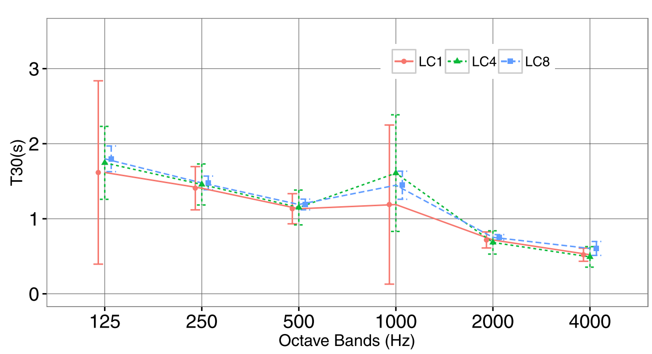

FIG. 5. (Color online) T30 for Las Chimeneas. Means and 95% confidence intervals are presented for measurements in three different sections within the cave.

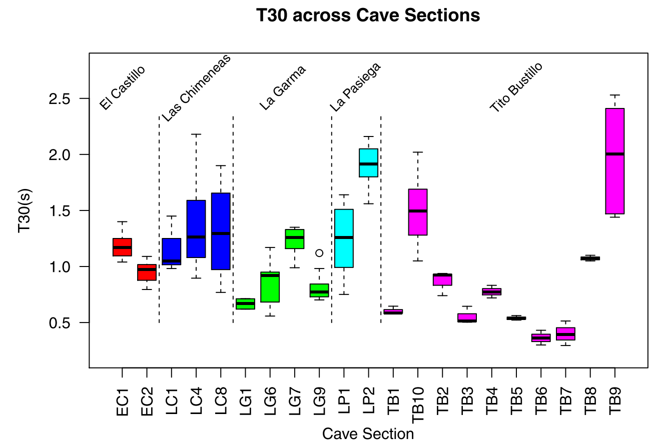

FIG. 6. (Color online) T30 boxplots showing median, interquartile range, maximum, and minimum values. Circles represent outliers. Data are shown for each section within the cave. Sections are grouped per cave with different shades.

obtained in the 500 and 1000 Hz octave bands. Average T30 values are contained between 0.2 s and around 1.2 s with two sections exhibiting T30 larger than 1.5 s. One of these measurements was taken in the very large central gallery of the Tito Bustillo cave. The other was in La Pasiega where two long corridors crossed. Both T30 and EDT relate to the time it takes for the energy in the space to decay by 60 dB. T30 accounts for this decay after the first 5 dB drop and is therefore not overly dependent on very early reflections and, consequently, to local conditions at each measurement position. On the other hand, EDT corresponds to the time taken for the energy to decay by 10 dB immediately after the arrival of the direct sound, making it more sensitive to early reflections and thus to local conditions (Barron, 2009). The values obtained for EDT in each section are similar to those for T30 albeit with a slight decrease, as would be expected since the early energy often decays more rapidly than late reverberation. These results are shown in Figs. 6 and 7.

The deeper parts of the caves, away from the entrance, were probably used for ritual purposes rather than occupation (which was mostly near cave entrances: Arias, 2009),

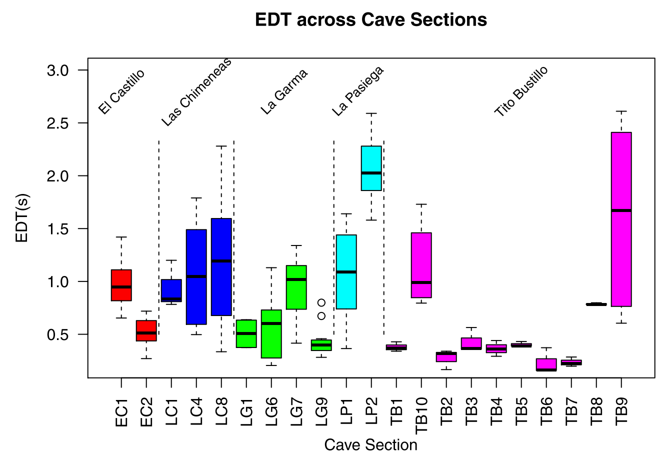

FIG. 7. (Color online) EDT boxplots showing median, interquartile range, maximum, and minimum values. Circles represent outliers. Data are shown for each section within the cave. Sections are grouped per cave with different shades.

and thus metrics widely used in acoustic description of contemporary ceremonial spaces such as concert halls and churches are used here to provide a well-grounded comparison between the conditions found in caves and those found in the modern built environment. These metrics, calculated from the measured impulse responses, relate to the way the reflected energy is distributed over time and define aspects of speech intelligibility (STI), clarity for musical sources in concert halls (C80), and the *distinctness of sound* or definition (D50) (Kuttruff, 2009). These are typical acoustic metrics, often used to describe the performance of spaces where acoustic performances involving either spoken word or musical activity are to take place. The average values for C80 and D50 have been obtained from the measured values at 500 Hz, 1 kHz, and 2 kHz as per Barron (2009). The values for STI have been obtained according to Steeneken and Houtgast (1980).

The extracted metrics for each cave section are presented as medians and interquartile ranges in Figs. 8, 9, and 10.

STI across the measurement positions lies within 0.5 and 0.9, which is a range where STI is considered "good" or better. C80 values range between -1 and 20 dB. The preferred range for this metric in auditorium acoustics is above -2 dB (Barron, 2009). D50 ranges from around 0.3 to around 0.9. The preferred range for this metric is above 0.5. Overall, the values found in the caves indicate conditions with good clarity and, mainly, intelligible speech. If these were modern auditoria they might be described for example as offering favourable conditions for musical activity. Hence most measurements within the caves indicate spaces without the typical acoustic problems, such as echoes or over-long reverberation, which are known to mask certain aspects of sound in communication (speech in particular) and to interfere with music making (Barron, 2009; Kuttruff, 2009).

V. STATISTICAL ANALYSES

To investigate associations between the position of motifs and the acoustic response at these positions, statistical models were fitted to the acoustic data in order to compare that with data on the presence of motifs and their type. Models of this kind generally require a significant number of samples in order to ensure sufficient statistical power for a valid test. Initial analyses focused on responses obtained in each cave but did not reveal statistically significant data owing to low sample count and, in the cases of El Castillo, La Garma, and La Pasiega, to the lack of sufficient samples in control positions, i.e., at places where no motifs are found. Indeed, at Las Chimeneas there were no positions without motifs except at the collapsed original entrance. Our interest, however, lies in the association between the behavior of those who created the motifs and the acoustic response they would have experienced when near to the motifs. The dataset has therefore been collated to allow a meta-analysis across all five caves. This results in a significant count of data samples ($N = 177$) and the statistical analyses thus exhibit higher power. Such integration of data also makes sense archaeologically, as the caves are situated within a restricted geographic region, and the motifs that they contain belong to a shared series of cultural traditions.

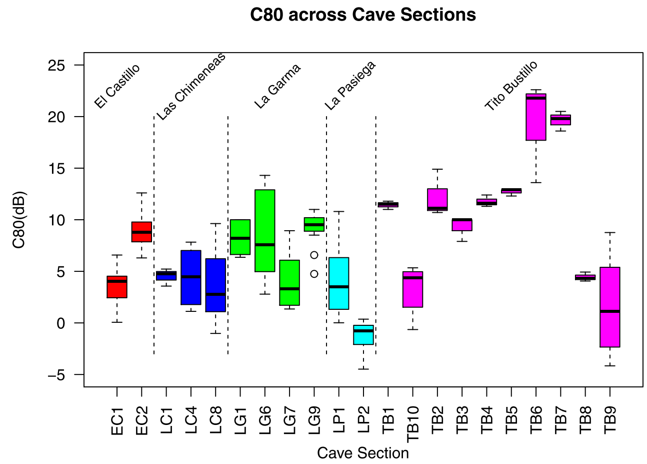

FIG. 9. (Color online) C80 boxplots showing median, interquartile range, maximum, and minimum values. Circles represent outliers. Data are shown for each section within the cave. Sections are grouped per cave with different shades.

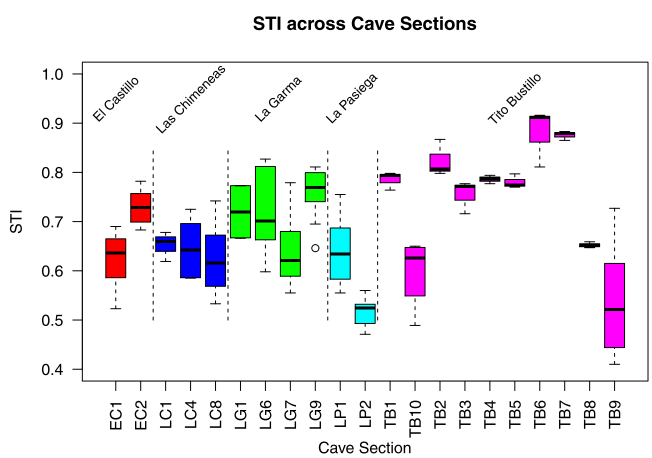

FIG. 8. (Color online) STI boxplots showing median, interquartile range, maximum, and minimum values. Circles represent outliers. Data are shown for each section within the cave. Sections are grouped per cave with different shades.

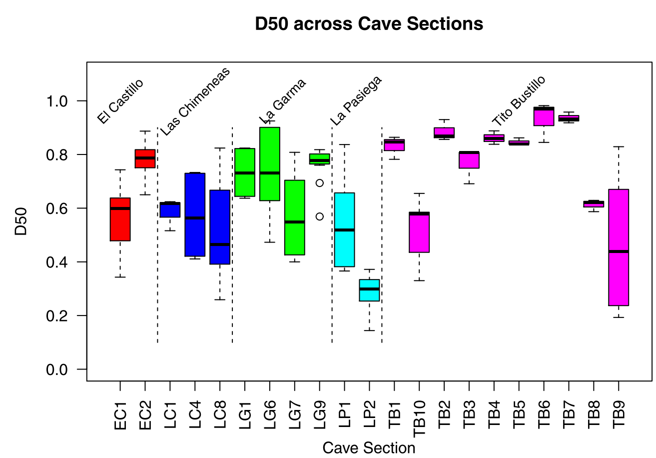

FIG. 10. (Color online) D50 boxplots showing median, interquartile range, maximum, and minimum values. Circles represent outliers. Data are shown for each section within the cave. Sections are grouped per cave with different shades.

A. Building an explanatory statistical model

The purpose of the statistical analyses that follow is to build an explanatory model and test whether the acoustic variables in this model have a statistically significant relationship to the human behaviors under study. These behaviors are selected based upon the following research questions:

(1) Is there an association between motifs of the earliest phase and acoustic response? This first investigation focuses on dots and lines, followed by an analysis of hand stencils, which are also early in date.
(2) Is there an association between acoustic response and motifs across all three periods under study: early, middle, and late? This considers whether the chronological categorization of motifs can be explained by the acoustic response.
(3) Can the color of motifs be explained by acoustic response?
(4) Is there an association between acoustic response and the position of any type of motif, regardless of its type, color, or era? This analysis is divided into two parts. First, it explores situations where the acoustic response is individually associated with a motif within a 1 m radius. Second, it (re)codes acoustic measurements taken within an entire section of the cave, according to the presence or absence of motifs within that section. As we will see, this difference in coding has an effect on the explanatory power of the statistical model.

The final statistical model explores whether factors other than acoustic response (such as proximity to the original cave entrance) might aid in explaining the positioning of motifs. This puts in perspective the relative importance of variables other than those reporting acoustic response metrics in explaining the position of motifs.

For the analyses listed above, the dependent variable is either dichotomous (presence or absence of motifs), categorical (e.g., animal, hands, or dots for type of motifs) or ordinal (early, middle, and late era). For variables of these kinds, binary logistic regressions, multinomial logistic regressions, and ordinal logistic regressions, respectively, are suitable models, and it is these that are the object of the analyses that follow. Given the sparse number of samples for each condition, normal distributions of data cannot be assumed and the more typical and powerful parametric analyses cannot be applied.

Where statistically significant models can be found, they define the probability that the dependent variable is a function of the explanatory (i.e., independent) variables. In lay person's terms, this tests whether there is a statistical association between acoustic parameters and motif-related parameters, and also quantifies the statistical probability of that relationship. The data collected have been tested for compliance with the underlying assumptions required by these statistical models, and those assumptions have been met in all cases presented. Particular tests for this are indicated where appropriate. The data for the study are available and may be downloaded from https://tinyurl.com/n5pmm8m, citing this paper as the source.

As mentioned previously, details of every acoustic response sampled were recorded on a spreadsheet. At each position a range of data was collated, including presence, shape, color, position, and date of motif. Every measurement contains coding of archaeological data, and hence in the simplest categorization, the binary presence/absence of a motif near the position of the acoustic measurement is known. For this categorization, the existence of a motif within 1 m of the measurement microphone means that that particular measurement position is coded as *motif present*.

Data cases (177) have been collected in the five caves studied. A binary coding has been applied for the following variables:

Presence/absence of motif ($N = 177$; Yes = 98, No = 79).
Presence/absence of dots-lines ($N = 177$; Yes = 64, No = 113).
Presence/absence of hand stencils ($N = 177$; Yes = 16, No = 161).

For all cases where motifs are present, the relevant archaeological data within the sample were coded. The categorical variables in these cases are (sample counts in each category):

Chronology: early, middle, late (26,30,38).
Type: dots-lines, animals, hand stencils, symbols (64,27,5,2).
Color: black, red, violet (27,52,8).

B. Reducing the number of variables

Twenty-three different acoustic metrics were extracted from each of the impulse responses, as discussed in more detail in Sec. IV above. Most of these are correlated, meaning there is redundancy in the set (i.e., some of these 23 metrics provide very similar information). Furthermore, performing the following statistical analysis on each of the 23 variables individually would ignore relationships and interaction effects between the variables. In order to reduce the data, a Principal Component Analysis (PCA) has been performed. PCA is a dimensionality reduction technique which here allows a more useful interpretation of the acoustic data, grouping the granular information into principal components or *dimensions*, which more directly explain the variance found in the dataset with regards to acoustic response. The dimensions provided by the PCA can be seen as synthetic variables that contain within them the contributions of each of the original acoustic metrics extracted from the measurements. These dimensions will, however, be one step removed from those original acoustic metrics (such as T30, EDT, and STI) making the interpretation of results somewhat more complex.

A number of assumptions are made for the PCA. It is assumed that all variables submitted to the PCA are continuous and that a linear relationship exists between most variables. This has been tested using a correlation matrix, and most variables are correlated at 0.9 or above, while the lowest correlation value found is 0.08. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.909, suggesting that a PCA is adequate for this dataset. Using Bartlett's test of sphericity, the null hypothesis that the correlation matrix of the data is equivalent to an identity matrix was rejected ($\chi^2 = 11\,842$, df = 253, $p < 0.000$) indicating good suitability for data reduction. Outliers have been checked by comparing the mean with the 5% trimmed mean (Sarkar *et al.*, 2011). For all variables the difference between the two means was below or much below 5% of the original mean, except for LFdevflat and LFdevsmooth where the difference was 12% and 8% of the original mean, respectively. No variables were therefore removed.

The initial unrotated PCA reveals three dimensions explaining 87.5% of the total variance in the data. A null hypothesis test for the correlation between dimensions was shown to be highly significant (all $p < 0.000$) suggesting no significant correlation between the three extracted dimensions. A further PCA was thus limited to three dimensions, and rotated using the Varimax method. Here dimension 1 explains 72% of the variance whilst dimensions 2 and 3 explain 11% and 4.5%, respectively. The results of the rotated PCA will now be discussed.

Figures 11 and 12 show the three principal components, or dimensions, extracted from the acoustic data. The *loading* of each acoustic metric on each dimension can be obtained from the projection of its vector onto the corresponding dimension axis. For example, in Fig. 11, variables related to reverberation (T30, EDT) load strongly in the positive direction of dimension 1, while clarity, definition, and STI (C80, D50, and STI) load strongly in the negative direction. The resultant PCA indicates this loading as a correlation coefficient (ρ) between each of the metrics and each of the extracted dimensions. In detail, the highest significant correlations are found for metrics based on T30 ($\rho \approx 0.98$, $p < 0.01$) and EDT ($\rho \approx 0.98$, $p < 0.01$) in the positive direction, and STI ($\rho \approx -0.97$, $p < 0.01$), D50 ($\rho \approx -0.96$, $p < 0.01$), and C80 ($\rho \approx -0.94$, $p < 0.01$) in the negative direction of dimension 1. Dimension 1 thus appears to describe aspects of energy decay, with large positive values corresponding to very reverberant responses whereas large negative values correspond to responses with very low reverberation.

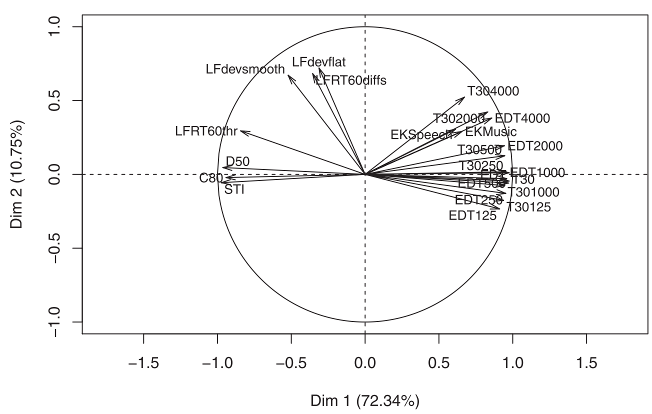

FIG. 11. Dimensions 1 and 2 resulting from the PCA of the 23 acoustic metrics. Metrics of energy decay (e.g., T30, EDT) and intelligibility (e.g., STI) load onto opposite ends of dimension 1, which explains 72% of the variance in the data. Metrics of merit of low frequency response (LFdevflat, LFRT60diffs, LFdevsmooth) load onto dimension 2, which explains 11% of variance in the data.

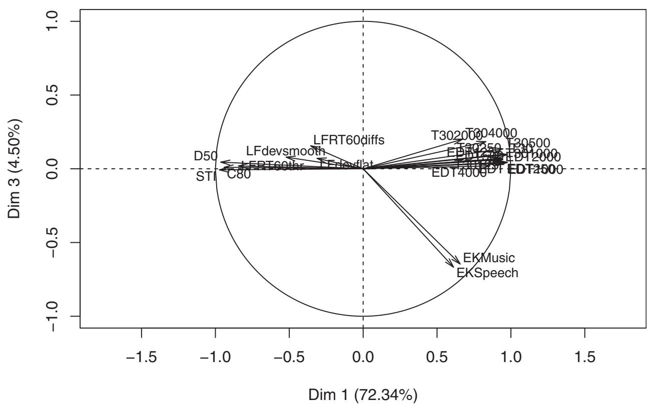

FIG. 12. Dimensions 1 and 3 resulting from the PCA of the 23 acoustic metrics. Echo criteria metrics (EKSpeech, EKMusic) load more strongly onto dimension 3, which explains 4.5% of variance in the data.

Dimension 2 has significant correlations with metrics reporting the low frequency response of the measurements—Lfdevsmooth ($\rho \approx 0.72$, $p < 0.01$), LFRT60diffs ($\rho \approx 0.68$, $p < 0.01$), and LFdevflat ($\rho \approx 0.67$, $p < 0.01$). This dimension thus appears to describe the merit of low frequency response of the spaces, where high values along this dimension correspond to spaces with "acceptable" low frequency response, whereas low values correspond to spaces that deviate from "optimal" low frequency response (as defined for modern sound reproduction spaces) and might therefore exhibit audible modal behavior or, as they are commonly known, resonances.

For dimension 3, significant negative correlations are found for the two metrics used to detect echoes—EKSpeech ($\rho \approx -0.68$, $p < 0.01$) and EKMusic ($\rho \approx -0.65$, $p < 0.01$). It thus appears this dimension is associated with evidence or otherwise of audible echoes. Larger values along this dimension indicate the presence of echoes in the acoustic response. Importantly, further analysis of the tabulated raw data obtained for each measurement shows that none of the values obtained for the echo metrics were found above the echo audibility threshold, demonstrating that audible echoes have not been found in this dataset. This is corroborated by the low value of variance explained (4.5%) by this third dimension. It is nonetheless interesting to observe that metrics for echo detection form a dimension that is distinct (orthogonal) from the first two principal dimensions.

The dimensions identified will be the basis for further analysis, and it is useful therefore to summarize their interpretations. Those are shown in Table III.

Figure 13 shows the position of each data sample (acoustic measurement) along dimensions 1 and 2 and its categorisation according to whether a motif is present at the measurement point or not. The 95% confidence ellipses are also plotted for each category and provide an indication of significant differences between these. The presence or absence of motif is coded in a different shade (color online). The non-overlapping ellipses suggest there are statistically significant differences between the two categories along each of the dimensions. It can be further observed that data points associated with motifs appear to be concentrated toward the central values, particularly along dimension 1,

TABLE III. Variance explained for each dimension extracted through a PCA of the 23 acoustic metrics used in the study. An interpretation is provided on the basis of the acoustic metrics which more strongly load onto each dimension.

Dimension	Variance explained	Interpretation
1	72%	A measure of energy decay. Large positive values along this dimension are represented by spaces with larger values of reverberation (T30, EDT). Large negative values are represented by spaces with high clarity (C80), definition (D50), and STI.
2	11%	A measure of low frequency response merit. Large positive values along this dimension correspond to spaces approaching optimal low frequency behavior as defined for modern sound reproduction in rooms. As the value of this dimension decreases, the associated spaces deviate significantly from optimal low frequency response and may therefore exhibit audible modal behavior.
3	4.5%	A measure of presence or absence of echoes. Less negative values suggest the presence of echoes.

while data points where no motif is present seem to occur over a larger range of this dimension. In other words, the density of points associated with motifs is larger where energy decay is moderate, neither too high nor too low. Motifs appear less likely to be present in those positions that are either very reverberant or very dry. This suggests a quadratic distribution for this dimension. Given this observation, a transformation of the dimension 1 variable into its square was also included in the statistical analysis below. This thus defines a fourth variable in the model, which explores the likelihood of extreme or central values along dimension 1.

C. Dots and lines

Dots and lines are currently believed to be the earliest motifs in these caves. The following statistical model explores whether their location is associated with the acoustic response. To investigate this, the data have been coded on a presence/absence basis [dots-lines = 64; none (control) = 113]. Note here that any positions coded as having motifs that are not dots or lines (such as animal images) have been grouped with the control positions, since these motifs were probably added at a later date. The statistical model chosen to analyze the data is the logistic regression, which is represented as

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4}, \quad (1)$$

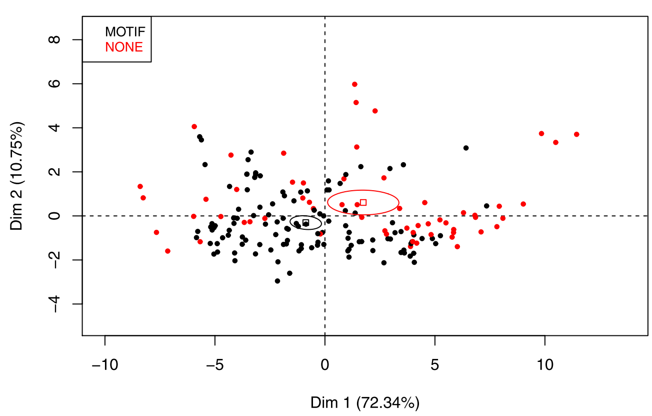

FIG. 13. (Color online) Individual samples (measurements) along dimensions 1 and 2. Ninety-five percent confidence ellipses are also plotted for both motif and no-motif data sets. The non-overlapping ellipses show significant differences between the two categories (motif, none) along each of the dimensions.

where p_i is the probability of finding a dot or line, x_{i1}, x_{i2}, and x_{i3} are independent variables associated with the three dimensions identified in the original data using PCA, and x_{i4} is a square transformation of dimension 1, representing an independent variable in the model which accounts for its apparent quadratic distribution. The dependent variable in this analysis is presence/absence of dots or lines at each measurement point, so the model calculates the probability of finding dots or lines at a specific location given the values of acoustic metrics at that location.

A logistic regression was performed to ascertain the effect of each of the independent variables on the likelihood that a dot and/or line will be found at a particular position. The logistic regression model was statistically significant, $\chi^2(4) = 25.126$, $p < 0.0005$. The model explained 18.1% (Nagelkerke R^2) of the variance in the presence/absence of a dot/line and correctly classified 71.2% of cases. It was found that the probability of finding a dot or line decreases with increasing values of dimension 1 ($\beta_1 = -0.41$, $e^{\beta 1} = 0.664$, $p < 0.05$). The $e^{\beta 1} = 0.664$ indicates the odds that a dot and/or line will be found if the measured value for dimension 1 increases by one unit (after controlling for the other factors in the model). The interpretation of odds here, reporting effect size, is consistent with the typical interpretation of logistic regression results. For example, given that logistic regression outputs the natural logarithm of the odds, the exponential of the coefficients represents the result of the odds ratio. Odds are easier to interpret if they are presented as values above 1, indicating the likelihood of an event. Decimal odds (below 1) can be inverted (i.e., $1/e^{\beta\#}$) as long as their interpretation is adapted accordingly. Applying this principle to the result above ($1/e^{\beta 1} = 1/0.664 = 1.5$), we can infer that dots or lines are 1.5 times more likely to be found if the measured value in dimension 1 *decreases* by one unit. In other words, as reverberation decreases and clarity/definition/STI increases, it becomes more probable that dot or line motifs will be found. Measurement positions near dots/lines have a T30 in the range of 0.6 s to about 1.7 s, whereas T30 at control positions may be as low as 0.3 s and as high as 2.53 s.

The statistical model further shows that an increase in dimension 2 makes it statistically less likely that a dot or line will be found ($\beta_2 = -0.773$, $e^{\beta 2} = 0.462$, $p < 0.05$). Following the principle introduced in the previous paragraph, as the value of dimension 2 *decreases* by one unit for a given acoustic measurement position, it is twice as likely ($1/e^{\beta 2} = 1/0.462 = 2.2$) that dots and/or lines will be found there. This result suggests that dots or lines are more probable in places with resonant artefacts, since dimension 2 reports on the existence of resonances for low values.

The variables associated with dimension 3 (x_{i3}) and the square of dimension 1(x_{i4}) were not found to be significant in this model ($p > 0.05$). There is thus no evidence that the positions of dots or lines are associated with the presence of audible echoes.

In summary, these results show some evidence that it is statistically more probable to find dots and lines in places where reverberation is not high and where the response is more modal thus sustaining potentially audible resonances.

D. Hand stencils

Hand stencils belong to the early period of cave motifs, and from the evidence of U-series dating of calcite formations, may be as old as dots and lines (Pike *et al.*, 2012). To investigate whether there is an association between the positions of hand stencils and acoustic response, the data have been recoded to examine the presence/absence of motifs included in this category. Measured positions without hand motifs were categorized as "no motif" ($N = 177$; Hands = 16, None = 161).

A logistic regression was performed to ascertain the impact of each of the acoustic dimensions on the likelihood that a hand stencil will be found at a particular position. The logistic regression model was statistically significant, [$\chi^2(4) = 16.371$, $p < 0.0005$]. It explained 19.4% (Nagelkerke R^2) of the variance in the presence/absence of a hand stencil. Although the model correctly classified 91% of cases, this arises because it predicts that all instances have no motifs and fails to predict any of the instances where a motif is present. Since the latter (locations with hand stencils) are much more rare in this dataset, the model appears to have a high correlation with the data but this is merely a mathematical artefact (see Table IV). Grouping the results for hand stencils with those of dots and lines together was explored, but provided no additional explanatory power, i.e., the model was identical to the one obtained for dots-lines save that its explained variance decreases slightly. We cannot therefore infer that the positioning of hand stencils has a statistically significant association with acoustic metrics.

E. Chronology, type, and color of motifs

The motifs in these caves have been divided chronologically into three periods: early, middle, and late, as described in Sec. III B. In analyzing the association between the chronological period of motifs and the acoustic response, the dependent variable is polytomous and has three levels. An ordinal logistic regression in which date is the dependent variable, with three levels, has therefore been performed. The independent variables were the same four acoustic variables as before (dimensions 1, 2, and 3 and dimension 1 squared). In this case, the result of the model fit χ^2 test is not significant ($p > 0.05$) and therefore an ordinal regression model of association between age of motif and acoustic response was not substantiated.

The association between type of motif (Animal = 27, Dot/Line = 64, Hand = 5, Symbol = 2) and acoustic response was modelled using a multinomial logistic regression. The model fit again was not significant [$\chi^2(9) = 10.8$, $p > 0.05$] and hence none of the factors in the model were found to be significant. An association between the type of motif and acoustic response was not found.

A multinomial logistic regression analysis was run to check for an association between color of motif (black = 27, red = 52, violet = 8) and the acoustic response measured at that position. Again, the model fit was not significant [$\chi^2(6) = 10.9$, $p > 0.05$]. An association was thus not found between the color of motif and acoustic response.

F. Presence or absence of motifs in general—position dependent

In addition to exploring relationships between specific categories of motif and acoustic response, a final analysis was undertaken to investigate whether there is statistical evidence that the location of a motif (regardless of date or type) might be associated with particular acoustic responses. We have seen that dots and/or lines are more likely to be found in locations with low reverberation and resonant artefacts. Here we carry out a similar analysis but consider the presence/absence of any motif as our dependent variable. The independent variables are the same as in Eq. (1).

A logistic regression produced a statistically significant model, $\chi^2(4) = 34.001$, $p < 0.0005$. The model explained 23.4% (Nagelkerke R^2) of the variance in the presence/absence of a motif and correctly classified 68.4% of cases. Variables in this model can be seen in Table V.

It was found that the probability of finding a motif decreases with increasing values of dimension 2 ($\beta_2 = -0.54$, $e^{\beta 2} = 0.582$, $p < 0.05$). This result is similar to that noted earlier for dots and lines. In this case motifs are 1.7 times more likely to be found in places exhibiting a more modal

TABLE IV. Classification table for logistic model predicting the presence of hand motifs according to acoustic response. It can be seen that the high percentage of identification comes from the model predicting all instances as belonging to no presence of the hand stencils. As places with no hand stencils are disproportionally more represented within our dataset, the predictive power of the model is misleading and, as such, cannot be relied upon.

Hand stencils	Observed	Predicted (%)
0	161	100
1	16	0
Total	**177**	**91**

TABLE V. Logistic regression model for data where motif presence is coded at individual positions. B is beta coefficient. S.E. is standard error, df is degrees of freedom, Sig. is significance, and Exp(B) is the odds ratio.

Variables in the Equation	B	S.E.	Wald	df	Sig.	Exp(B)
Dimension 1	−0.357	0.190	3.537	1	0.060	0.700
Dimension 2	−0.540	0.182	8.812	1	0.003	0.582
Dimension 3	−0.008	0.170	0.002	1	0.965	0.992
Dimension 1 squared	−0.766	0.212	13.117	1	0.000	0.465
Constant	0.884	0.239	13.648	1	0.000	2.421

response. The odds have decreased because now we are looking at any type of motif, rather than only dots or lines. This small drop in effect size may, perhaps, suggest that the addition of any type of motif to the dots-lines category weakens the statistical association which exists mainly for dots-lines but is less strong for other, later motifs.

It was further observed that an increase in x_{i4}, the square of dimension 1, makes the presence of a motif less likely ($\beta_4 = -0.766$, $e^{\beta 4} = 0.465$, $p < 0.05$). That is an interesting result which suggests that motifs are *twice* ($1/0.465 = 2.15$) more likely to be found if the value of this dimension decreases by one unit, after controlling for other factors in the model. It means motifs are more common in places of moderate reverberation—neither very high or very low (because x_{i4} has large values at either extreme of dimension 1). This indicates that motifs are mainly found in positions where a balance between reverberation and clarity is present (avoiding high levels of reverberation, but where metric scores pertaining to intelligibility, clarity, and definition also are not high).

G. Presence or absence of motifs in general—cave section dependent

So far, the presence/absence of a motif has been coded on whether that motif is found within a radius of 1 m from the measurement microphone. This is more restrictive than Reznikoff's coding which used a 2 m radius (Reznikoff, 2002: p. 43). Use of a 1 m radius presumes that any notable acoustic effects that might influence the location of a given motif would be perceived only in that precise position. This might not always be the case. Although low frequency resonance is often tightly localized, reverberation is associated with diffuse fields, meaning its effects are spread equally across a large space. Thus it might be argued that in some cases, the presence or absence of motifs should be assessed in relation to all measurement positions within the same section of acoustic space. Such analysis might reveal whether the acoustic response of sections of caves where motifs exist differs significantly from that in other sections where no motifs are found.

The 177 original measurement points were thus recoded to Motif = 136 and No Motif = 41, where the coding for *presence* of motif was defined on the basis that the measurement was taken in a section of the cave which had at least one motif present. In such cases, measurement points might be several meters distant from motifs but within the same physically enclosed space, in other words, the same *section* of the cave. In this stage of the analysis, many measurement positions, even those not immediately adjacent to a motif, will be grouped as "motif present."

Figure 14 shows the distribution of the data along acoustic dimensions 1 and 2 ordered according to this latter definition.

A logistic regression model was calculated using the same independent variables as in Eq. (1), but with the data points recoded in terms of their membership to a particular cave section rather than specific proximity to a motif. A statistically significant model was found, $\chi^2(4) = 26.888$, $p < 0.0005$. The model explained 21.3% (Nagelkerke R^2) of the variance in the presence/absence of a motif and correctly classified 80.2% of cases. The explanatory power of the model has decreased slightly from that presented in Sec. V F. The model variables can be seen in Table VI.

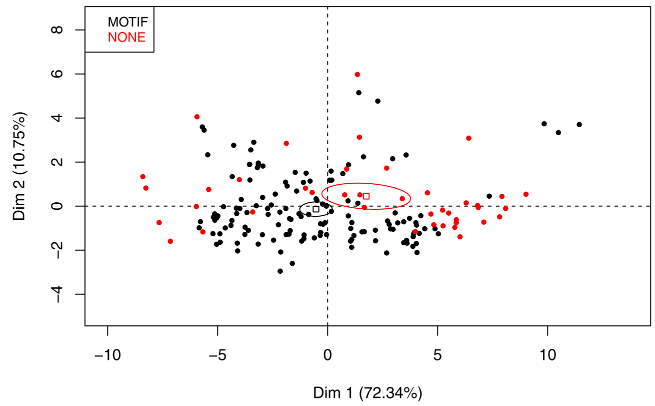

FIG. 14. (Color online) Individual samples (measurements) along dimensions 1 and 2, with data grouped by sections within each cave. Ninety-five percent confidence ellipses are also plotted for both motif and no-motif data sets. In contrast with data coded individually, there is a substantial overlap between 95% confidence ellipses suggesting that significant differences between the two categories (motif, none), particularly along dimension 2, are no longer present.

Interestingly, the only significant variable in this model is x_{i4}, the square of dimension 1, and this is further supported by the increased overlap of ellipses observed in Fig. 14. It was found that the probability of finding a motif decreases with increasing values of x_{i4} ($\beta_4 = -0.585$, $e^{\beta 4} = 0.557$, $p < 0.05$). A motif is 1.8 ($1/0.557 = 1.8$) times more likely to be found for every unit decrease of dimension 1 squared. This result is similar to that already observed in Sec. V F, i.e., that motifs are more likely to be present in places with moderate values for reverberation.

It should be noted that the variable associated with dimension 2, x_{i2}, is no longer significant in this model, suggesting that under these new assumptions the presence/absence of motifs is no longer statistically associated with low frequency resonances. Acoustic theory indicates that modal effects in rooms are localized within a physically enclosed space (Kuttruff, 2009), but grouping all the measurements in a given section together has effectively averaged out those effects. In contrast, the metrics associated with x_{i4}, which by theoretical definition assume a more homogeneous distribution across spaces, retain their significant explanatory power.

TABLE VI. Logistic regression model for data where motif presence is coded as a function of cave section. B is beta coefficient. S.E. is standard error, df is degrees of freedom, Sig. is significance, and Exp(B) is the odds ratio.

Variables in the Equation	B	S.E.	Wald	df	Sig.	Exp(B)
Dimension 1	−0.363	0.191	3.611	1	0.057	0.696
Dimension 2	−0.296	0.194	2.320	1	0.128	0.744
Dimension 3	−0.136	0.200	0.464	1	0.496	0.873
Dimension 1 squared	−0.585	0.186	9.898	1	0.002	0.557
Constant	1.889	0.282	45.023	1	0.000	6.612

H. Other variables in the model—proximity to the original entrance

So far, the model that best explains the position of motifs from the acoustic metrics has a 23.4% explanatory power, identifying low frequency resonances and reverberation or lack thereof as significant variables(Sec. V F). 23.4% is a somewhat low level of explanatory power, and it is important to consider other systematic factors that may have an association with the placement of a motif in a given location. Such a factor, which has been included in the field measurements, is distance from the original cave entrance. We recorded data on the distance between the original entrance of each cave and each of the motifs, and included this data as an added variable in our "best fit" model established in Sec. V F. The new logistic regression model hence contains one additional variable, x_{i5}, representing distance of motif from cave entrance:

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4} + \beta_5 x_{i5}. \quad (2)$$

The resulting model was statistically significant [$\chi^2(5) = 45.065$, $p < 0.0005$]. The model explained 30.1% (Nagelkerke R^2) of the variance in the presence/absence of motifs and correctly classified 72.3% of cases. Table VII shows the variables in the model. Significant variables are x_{i1} ($\beta_1 = -0.635$, $e^{\beta 1} = 0.530$, $p < 0.05$), the dimension describing energy decay and intelligibility/clarity/definition; x_{i2} ($\beta_2 = -0.505$, $e^{\beta 2} = 0.604$, $p < 0.05$), the dimension describing low frequency response; x_{i4} ($\beta_4 = -0.768$, $e^{\beta 4} = 0.464$, $p < 0.05$), the square of dimension 1; and x_{i5} ($\beta_5 = -0.006$, $e^{\beta 5} = 0.994$, $p < 0.05$), corresponding to distance, in meters, from the measurement position to the original cave entrance.

The significant variables are once again inversely correlated to the presence of motifs. The added observation from this analysis is that one is less likely to find motifs in measurement positions deeper into the cave ($\beta_5 = -0.006$, $e^{\beta 5} = 0.994$, $p < 0.05$). Controlling for each of the other variables, we can interpret that motifs are: 1.9 times more likely to be found when dimension 1 decreases by one unit; 1.6 times more likely to be found when dimension 2 decreases by one unit; 2.1 times more likely to be found when the square of dimension 1 decreases by one unit; and 1.006 times more likely if the distance to the original entrance decreases by 1 m.

TABLE VII. Logistic regression model for data where motif presence is coded at individual positions. The variable "distance to entrance" has been included in the model. B is beta coefficient, S.E. is standard error, df is degrees of freedom, Sig. is significance, and Exp(B) is the odds ratio.

Variables in the Equation	B	S.E.	Wald	df	Sig.	Exp(B)
Dimension 1	−0.635	0.215	8.710	1	0.003	0.530
Dimension 2	−0.505	0.198	6.479	1	0.011	0.604
Dimension 3	0.015	0.180	0.007	1	0.935	1.015
Dimension 1 squared	−0.768	0.212	13.115	1	0.000	0.464
Dist. to entrance	−0.006	0.002	10.372	1	0.001	0.994
Constant	1.594	0.339	22.076	1	0.000	4.921

A curious result is that both dimension 1 and its squared transformation are now significant. That indicates that, in this model, dimension 1 contains both linear and quadratic components. The conclusion from this result is that motifs are found where RTs are low, but not extremely low, suggesting a "bliss point" in the data (Moskowitz, 1981).

The inclusion of the distance variable and the consequent increase in the explanatory power of this model suggest that factors other than acoustic response will be significant in explaining an organized positioning of the motifs.

VI. DISCUSSION OF RESULTS

A. Acoustic response

The general acoustic response measured within the five caves studied here reveals reverberation and EDTs within a range from about 0.2 s to an average of 1.5 s with a few sections, particularly large in volume, revealing values above 2.5 s. Despite the general belief that caves sustain very long RTs, the spaces we measured did not show any particularly long values. An explanation for this might be associated with the various passageways and rough surfaces that are found in most of the caves and sections we studied.

The ranges measured for acoustic metrics within these caves show spaces with favorable conditions for speech and music (as defined according to modern criteria) indicating that any acoustic activity would have been accompanied by acoustic effects such as reverberation and levels of intelligibility that were neither limited nor excessive.

Reduction of variables from the 23 acoustic metrics extracted from the impulse responses collected in these caves has revealed that acoustic data are distributed along three major orthogonal dimensions:

- Dimension 1, explaining 72% of the variance, describes a measure of energy decay with large positive values representing higher reverberation (T30, EDT) and large negative values representing high values of clarity (C80), definition (D50), and STI.
- Dimension 2, explaining 11% of the variance, describes a measure of low frequency response merit with large positive values along this dimension corresponding to spaces approaching optimal low frequency behavior (as defined for modern sound reproduction in rooms) and negative values representing resonant behavior in the response.
- Dimension 3, explaining 4.5% of the variance in the data, describes evidence for audible echoes.

B. Association between acoustic response and motifs

Statistical associations between the positioning of motifs and acoustic response were found in several of our analyses. These include statistically significant associations between the presence of dots and lines, the earlier type of motifs, and dimensions 1 and 2. The analysis showed that lines and/or dots are more likely to be found at places with low reverberation and high clarity/definition and STI, and where there is evidence for low frequency resonances. The effect size for this association was small at (Nagelkerke) $R^2 = 0.181$ and the odds ratios calculated, giving a sense of effect size, were all in the small range (i.e., <3.5).

A statistically significant association was found between the presence of motifs in general, regardless of type, color, or period, and acoustic response. The significant variables in these associations were again associated with dimensions 1 and 2, i.e., the degree of reverberation, intelligibility, clarity, and definition and the degree of low frequency resonance in the response. In line with results for dots and lines, it was found that any motif is more likely to be located at places where reverberation is low and intelligibility, clarity, and definition are high and where low frequency resonances might be audible. Here again, the odds ratio calculated was found to be in the small range, always below 2.5.

Perhaps more intriguingly, our best model suggests that motifs are more likely to be found at places where indices of reverberation are moderate, rather than too high or too low, suggesting an optimal region. The explanatory power of the best statistical model fitted to this data is 30.1%, which is not very high, and might warn against inferring very strong conclusions from these results. This statistical model contains variables accounting for the behavior of the two main dimensions representing the acoustic metrics as well as a variable representing the distance from the acoustic measurement to the original entrance of the cave.

The results presented here both confirm and contradict some of the arguments made in previous studies by Waller (1993a,b) and Reznikoff and Dauvois (1988). On the one hand, there seems to be weak evidence of statistical association supporting the notion that motifs, and in particular lines and dots, are more likely to be found at places with resonances. This was Reznikoff's most confident conclusion (Reznikoff, 2006: p. 79). On the other hand, according to our analyses, motifs in general, regardless of type, color, or period, are less likely to be found at places with high reverberation. The effect size of this result was in the small range, which means the evidence of association exists but only weakly. Also, there is no evidence to suggest that echoes might have played a part, although this result is strongly influenced by the fact that we have not found any positions within these caves that sustained clearly audible echoes.

Employing a systematic and robust methodology, our study presents evidence that there is some statistical association between the positions of motifs and the acoustic response measured close to them, albeit at a weak statistical level. What has become clear is that if an appreciation of sound played a part in determining the position of motifs in these caves, it was only a part, since other aspects such as distance from the original cave entrance appear to have a significant relative weight, raising the explained variance in the model from 23% to 30%. Furthermore, the demonstration that distance from an entrance makes a significant contribution to the statistical model, suggests that a complex interaction of relationships is taking place.

No significant associations were found between chronology, or type or color of motifs, and the distribution of acoustic responses.

There are a number of possible aspects that affect the analysis and may play some part in explaining the weak statistical significance and effect sizes observed: there is a difficult archaeological context, with a 15 000 to 40 000 year distance to some of the material, the potential for not identifying positions with motifs due to deterioration, and the difficulty of working underground, in restricted time, within sites of archaeological significance, all producing significant challenges; the acoustic metrics used have been designed as descriptors of acoustic response in a modern built environment and while some have been shown to correlate to human response, they might not be the optimal metrics that can describe the experience of our ancestors in the context of caves; finally, the statistical models are sparse in terms of other architectural (contextual) factors that might have affected placement of motifs, such as porosity of the rock face and its accessibility.

VII. CONCLUSIONS

Blesser and Salter (2009) observe that, "cave wall images are tangible, enduring manifestations of (…) early humans," and that in contrast sound "has no enduring manifestation, nor of course could it have for any pre-technical peoples," meaning that as a result, "available data are too sparse to draw strong conclusions." Our contribution makes this data less sparse for the first time in a methodical and repeatable manner.

In our work, a statistical association has been established between acoustic response and the positions of Palaeolithic visual motifs found in these caves. Our primary conclusion is that there is statistical, although weak, evidence, for an association between acoustic responses measured within these caves and the placement of motifs. We found a statistical association between the position of motifs, particularly dots and lines, and places with low frequency resonances and moderate reverberation.

Importantly, we must reiterate that the statistically significant association does not necessarily indicate a causal relationship between motif placement and acoustic response. In other words, our evidence does not suggest that the positioning of motifs can be explained simply through relationships with acoustics, and we are not suggesting that motif positioning was based solely on an appreciation of sound properties. Indeed, we also found that motifs are statistically less likely to be found further into the caves, away from its original entrance, and this result further illustrates the complex relationship between early human behavior and features of these caves.

Rather than such simple associations, we suggest the interaction evidenced is subtle and complex, not one of basic causality, and that additional data are required for it to be fully understood. This is the first systematic study of this type, and further study is encouraged. Future research should aim to increase the size and quality of the dataset, by exploring more caves in Spain and France, particularly those visited by Reznikoff and Dauvois, as well as other cave systems in the world where this type of material culture exists; collecting a better balance between target and control positions, particularly for under-represented motifs such as hand stencils; investigating other aspects such as area and material properties of stone surface or volume of cave sections, which are directly related to acoustic response, but might also influence the decision to place a motif; and to further investigate aspects of the acoustic low frequency response in proximity to dots.

Musical instruments that have been found by archaeologists in caves that feature Palaeolithic motifs have provided some suggestions that ritualized musical activity might have been present in these spaces in prehistory in the same period when early human visual motifs were being created (Conard *et al.*, 2009; Buisson, 1990; García Benito *et al.*, 2016; Ibañez *et al.*, 2015). Our analysis presents empirical evidence that may be used to further investigate the suggestion of an appreciation of sound by early humans in caves that feature Palaeolithic visual motifs. The methodological challenge was to move beyond that general claim—that an appreciation of sound was relevant to cave rituals—and provide a methodology to evaluate the claim on a statistical basis.

The data collection and data analysis that we present here provide a new and robust approach, linking the physical properties of caves to early human behavior in a more rigorous and measurable way.

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