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Echoing landscapes: Echolocation and the placement of rock art in the Central Mediterranean

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ABSTRACT

Many societies give special importance to places where echoes are generated, and often these places receive special treatment including the production of rock paintings in them. The identification of the exact places where echoes come from, or echolocation, is an ability only shared by a few individuals in each community. Unfortunately for archaeologists, however, their activity leaves no trace in the archaeological record. In this article we propose that the Ambisonics technique, a method developed in the field of acoustical physics, can be applied to identify the likely use of echolocation among societies for which no ethnographic information remains, such as most of those who lived in prehistoric Europe. A description of how this method has been applied in two case studies, the rock art landscapes of Baume Brune (Vaucluse, France) and Valle d'Ividoro (Puglia, Italy), is provided. In these two echoing areas only a few shelters were chosen to be painted with Schematic art, leaving around them many others undecorated. In the description of the fieldwork phase of the test, issues related to the sound source, the sound recorder, and spherical camera and how the Impulse Response (IR) measurement was made are discussed. The processed results indicate that there was a positive relationship between sound-reflecting surfaces and the location of rock art. This leads us to propose that in both areas there is a strong probability of echolocation having been employed by Neolithic people to select the shelters in which to produce rock art. The results obtained in our study also have wider implications in our understanding of how prehistoric peoples perceived the landscape in which they lived in, understood not only on the basis of tangible elements but, perhaps more importantly, because of intangible aspects such as sound and, in particular, echoes.

1. Introduction

Are prehistoric rock art sites randomly located in the landscape? Archaeologists have answered this question by providing a range of reasons why this is not the case, and many of their answers are connected to functional elements in the landscape such as water or pathways (Bradley, 1997: chapter 5, Hartley and Vawser, 1998; Señorán Martín et al., 2014). In addition there are also other less measurable aspects noted, which scholars relate to symbolism and religious beliefs and link to special elements in the landscape such as mountain morphology, rock colour and also acoustics (Devereux, 2008; Díaz-Andreu, 2002; Díaz-Andreu and García Benito, 2015; Hameau, 1999; Mazel, 2011; Arsenault and Zawadzka, 2014; Ouzman, 2001; Steinbring, 1992). Many of the interpretations

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proposed by archaeologists have been based on information on modern hunter-gatherer and horticultural societies and this will also be the point of departure of this article. Many societies give special importance to places where echoes are generated, and often these places receive special treatment including the production of rock paintings in them. Modern studies in psychoacoustics demonstrate that some people have the capacity to locate places and orientate themselves by identifying the exact location where echoes and sound reflections came from. This ability, usually observed in blind people - but also in sighted people that have been trained-, is called echolocation (Kolarik et al., 2014, Teng and Whitney, 2011: Tables 1 and 2, Tonelli, et al., 2015).

Was echolocation used in the past? In order to answer this question one of the major difficulties that archaeologists are confronted with is that this activity either does not need any sort of material culture or, if any are used, these are friable and not very characteristic objects such as sticks and canes. Both in modern and traditional societies echolocation is achieved by echolocators – the individuals with the ability of identifying where the echo comes from – producing short, repetitive, impulsive and almost instantaneous sounds, such as tongue clicks, cane tapping sounds and handclapping. All these sounds have high peak pressure values, a quick rise time and a short duration, which means they do not interfere with the ensuing reflections (Arias et al., 2012; Rojas et al., 2009, Rojas et al., 2010).

In the field of rock art, the absence of material evidence related to echolocation has led specialists to look for indirect proofs connecting echoes and rock art. A high correlation between rock art sites and places where echoes are produced has been mentioned by several archaeologists. In most cases this correlation is made subjectively, based on appreciations of the auditory experiences of the researchers themselves at the sites (Steinbring, 1992; Reznikoff, 2002; 2014; Allan and Waller, 2009). A more objective approach has recently been introduced by Díaz-Andreu and García Benito (2012), Díaz-Andreu et al. (2014), and by Rainio et al. (2014). Both teams have based their tests in procedures developed in the field of acoustical physics, and it is in this line that the authors of this article, an interdisciplinary team of archaeologists and acoustic engineers, have been working for the last two years.

In this article we intend to develop a scientific methodology based on procedures developed in the field of acoustical physics related to the Ambisonics technique and adapted to fieldwork in open-air landscapes. This methodology will allow us to approach the question of whether echolocation was used by prehistoric populations in the selection and use of rock art sites. We will test our methodology in the Schematic rock art landscapes of Baume Brune (Vaucluse, France) and Valle d'Ividoro (Puglia, Italy). In both these areas, of the many available rock shelters, only a few were chosen by artists at the end of the Neolithic Age, raising the question of why these specific shelters had been selected.

2. Echoes and rock art in the literature

Echo, the repetition of sounds and words that often occur in mountainous areas, cliffs and distinct rocks, has fuelled superstitions and supported religious beliefs in many modern hunter-gather and horticultural societies all around the world. Echo possesses appealing qualities for people whose understanding of landscape is based on phenomenological aesthetics and aural experiences rather than physical laws. There are two compelling features of echo that are given special significance by many pre-modern societies. First, echo is the only natural means of reproducing and perpetuating human voices and artificial sound (Hollander, 1981: 1–2). Secondly, echo is a bodiless sound source, an animated voice that seems to emerge from behind the surface of reflecting planes. In pre-state belief systems where inanimate objects are perceived to be alive, echoing rocks are easily understood as the tangible evidence of numinous places dwelled by "talking" deities and supernatural creatures.

In the circumpolar area from Scandinavia to Canada, and also in the regions to its south, anthropologists and ethnographers have repeatedly recorded beliefs about echoing spirits dwelling within distinct rocks. In the Canadian Shield the manitous or "Memegwashio" – small human-like creatures that disappear inside cliffs and whose presence would be manifested by echoes (Bacon and Vincent, 1994: 45) – were credited as the makers of paintings and rock carvings (Dewdney and Kidd, 1962: 14, Conway and Conway, 1990: 27–29, Conway, 1993: 155–157, Shkilnyk, 1985: 71) (for other names received by the Memegwashio see Vaillancourt (2003): 113 note 59). Moving south, it has been noted in New Mexico that the Navajo's ceremonial use of the Tse'Biinaholts'a Yałti or 'Curved Rock That Speaks', a site with exceptional echoes (Loose, 2008) that displays rock art (Loose, 2010: 130). In the other extreme of the circumpolar area, in Scandinavia, prehistoric rock art has been found in some of these areas with special echoing effects showing the longevity of such beliefs (Lahelma, 2010: 50–52).

The importance of echoes in some rock art traditions implies the use of echolocation and the existence of echolocators. Evidence of echolocation, however, is difficult to find in the literature, although there are few exceptions. One of these is found in New Mexico, where among the myths that Leslie White gathered in his fieldwork of 1929–1930, there is one explaining how the Acoma people came to settle where they did. The story indicates that the twin leader, Masewi, looked for a place for their people to settle. In their wanderings

> they would pause at various mesas, thinking perhaps that they had found A'ko. Masewi would call out in a loud voice 'Aaaa-koooo-o-o !'. If the echo sounded favourable they would settle there for a time to make sure. But if the echo was not "good" they would pass on … When they came to the east point of Acoma, Masewi called out "A-a-a-ko-o-o-o!" and received a perfect echo. "This is Ako", he announced
>
> (White, 1932: 145).

Other relevant myths have been recorded among the Nuxalkmc in British Columbia (McIlwraith, 1948 (1992): 306, 323, Kramer, 2004: 166), and the Navajo (Bierhorst, 1974: 335, Matthews, 1902: 74, 114). In connection to beliefs related to echoes the existence of several name of places related to rocks that speak are to be noted in North America among the Cherokee (Mooney, 1900: 417), the Ojibwe (Ellis, 1880: 14–15) and the Iroquois (Speck, 1915:76). In Finland some cliffs rising from a lakeshore are considered sacred at least partly because of exceptional echoes (Paulaharju, 1932: 50 in Äikäs, 2015: 118).

3. Scientific methods to measure echoing rock art landscapes

How can echolocators find the place where the echoes come from? They do so by identifying the Direction of Arrival (DOA) of sounds reflections. There are two ways in which single or multiple sound reflections can reach the listener's ears: they can either arrive in a concentrated form from a specific DOA, giving the impression that the sound is reflected from a specific point in the landscape or, alternatively, they can arrive simultaneously at the listener's ears from different directions, conveying the impression of being enveloped by sound and inhibiting listeners from orientating themselves in that space on the basis of sound alone. In acoustics, the DOA of sound reflections can be measured by two methods, both commonly used by architectural acousticians to analyze the propagation of speech and music in theatres, concert halls, auditoriums and public spaces (Farina et al., 2007). The first method, the binaural technique, has been applied to the study of echoing rock art landscapes in Värikallio (Finland) by Riitta Rainio team (2014)'s. Instead, our team has favored the second method, the Ambisonics technique (Table 1).

Table 1
Differences between the Binaural and the Ambisonics technique.

	Binaural technique	Ambisonics technique
Employed by	Riitta Rainio et al. (2014)	Mattioli et al. (this article)
DOA of sound reflections	The Binaural technique inherently assumes that the reflected sound is coming from a single direction	The Ambisonics technique identifies all reflections at any time and direction
Methodology	The Binaural technique takes into account "time". More specifically, it triangulates the DOA of sound reflections by comparing the time of sound arrival (DTOA) (or Interaural Time Difference ITD) to two (or more) microphones	The Ambisonics technique takes into account "intensity". In particular it triangulates the DOA of sound reflections by comparing the intensity of sound waves arriving from every direction to a compact microphone array.
Results	Good results for horizontal angle (azimuth) of impinging reflections. Worse results for vertical angle (elevation).	Higher precision results for horizontal angle (azimuth) and vertical angle (elevation) of impinging reflections
Field usage	Troublesome because of size and complexity of the binaural equipment	High feasibility due to its compactness, great portability and cost-effectiveness. Much more precise in terms of angles accuracy (azimuth and elevation)

3.1. The binaural technique

The first method to measure the DOA of sound reflections, the binaural technique, makes use of the different time of arrival (TOA) of the sound pulse on a number of microphones placed at a significant distance from each other. It usually uses two microphones located at the ear canal entrances of a dummy head, by which the so-called Interaural Time Difference (ITD), or the difference in time of sound arrival (DTOA) at each of the human ears (Kunin et al., 2011), is calculated. From the DTOA, the approximate horizontal angle of arrival of echoes and reverberations (azimuth) can be estimated.

In the field of rock art research, the binaural measurement technique has been applied by Riitta Rainio and her team at the rock art site of Värikallio (Finland) (Rainio et al., 2014). This is a steep lake shore cliff with a massive smooth rock surface with paintings. The area was first surveyed acoustically by art historian and musicologist, Iégor Reznikoff, who argued that sounds, particularly echoes, may have played a central role in the selection of surfaces to be painted (Reznikoff, 1995: 551). Fieldwork in 2013 confirmed the presence of echoes. Rainio and her team measured the azimuthal-only DOA of sound reflections caused by the sound created by the firing of a blank pistol by comparing the DTOA of two omnidirectional microphones positioned 220 mm apart, a distance identified by this team as correlate to that between human ears. The results indicated that the area with the paintings acted as the most efficient sound reflector in the surrounding landscape. The rock art site reproduced "the impulse rather accurately in respect to the intensity, structure, duration and spectrum of the sound, even from afar", when on the other side of the lake (Rainio et al., 2014: 149). They also discovered a new motif probably representing a drummer, which they interpreted as a possible shaman on the basis of ethnographic source descriptions of shamans singing or chanting "at places that featured a prominent echo" (Rainio et al., 2014: 150). Although neither Reznikoff nor Rainio used the term echolocation in their papers, this concept was implied in their research.

3.2. The Ambisonics technique

The second method to measure the DOA, the Ambisonics technique, was evaluated for the first time in 1998 by one of the authors of this article (Farina and Tronchin, 1998) and was the one we decided to follow. The Ambisonics technique maps the intensity of sound waves arriving from every direction to a compact microphone array made up of a large number of directive microphones arranged over a spherical surface. The Ambisonics technique takes into account the variation in sound intensity coming from various directions. If referred to the human auditory system, this variation causes the so-called Interaural Level Difference (ILD) of sound intensity reaching each ear (Grantham, 1995; Gelfand, 2010). Both ITD and ILD are used by echolocators to infer information about the distance, angular location, size, shape and texture of the reflecting surface from which the sound reflections were generated (Pelegrin-García et al., 2015).

The Ambisonics technique has two major sets of advantages in contrast to the binaural technique. The first one is related to practical issues: the current size and complexity of the equipment needed for the binaural technique makes troublesome for field usage, especially in Mediterranean landscapes. The second set of advantages is technical, because the Ambisonics technique produces more precise measurements of angular readings of the DOA of echoes and reverberation than the binaural technique, as it has a higher sensitivity in the acquisition of both the horizontal and the vertical angle of arrival of sound reflections (azimuth and elevation). Furthermore, this method does not specifically require impulsive sound sources; the method can also be applied to assessing the spatial distribution of any kind of sound, including natural background noise or continuous sound. Hence, Ambisonics can be used to map the DOA of the reverberant tail, whilst the TOA method can only be applied to distinct echoes. Finally, through suitable post-processing of Ambisonics B-format signals, a quantitative energetic analysis of the sound field can be performed, providing an objective and quantitative indicator of the diffuseness of the reflected energy associated with the DOA of sound reflections.

In the remaining part of this article we present the first application of DOA measurements using the Ambisonics technique to rock art landscapes. In the following sections we describe in detail our experimental apparatus, starting from the choice of the sound source, the microphone array and how the latter was connected to a digital recorder and a panoramic camera. The post-processing phase is then explained, and this is followed by a discussion of the sound reflection DOA results obtained at the rock art landscapes of Baume Brune and Valle d'Ividoro.

4. A new "in situ" measurement technique for the three-dimensional characterization of echoes and reverberation in rock art landscapes

In room acoustics, the characterization of echoes and reverberation is based on the measurement of the so-called Impulse Response (IR). The IR measures the sound propagation from a sound emission point (sound source) to a receiver device (microphone), usually located within the same environment (Farina et al., 2007; Kuttruf, 2009: 255–261). In our tests we combined the receiver device with a spherical camera to acquire 360° × 180° panoramic pictures (photospheres). These pictures were then used in the post-processing phase as background images for the dynamic visualization of the DOA of sound reflections.

Fig. 1. The Brahma™ 1st-order Ambisonics tetrahedral microphone.

4.1. Sound source

A sound source is needed for measuring sound reflections. Following the rules accepted by the International Organization for Standardization (ISO), room acoustical parameters require omnidirectional sound sources and sound impulses covering at least the range of frequencies between 250 Hz and 2000 Hz with a peak sound pressure level (SPL) at least 35 dB above the background level (ISO 3382-1, 2009). Today, most acousticians use a variety of electrical signals as sound sources (e.g. exponential sine-sweep, maximum-length sequence) fed into a dodecahedron loudspeaker (optionally equipped with a subwoofer). This procedure, however, is extremely impractical for IR measurements in rock art landscapes; not only does it use expensive, heavy, bulky equipment, but it also needs a significant amount of electrical power, making it necessary to carry a huge battery pack or an electricity generator into the field. This is also the case of acoustical experiments undertaken in cave art research, which have encountered similar problems (Till, 2014: 297). Furthermore, the omnidirectionality of a dodecahedron is quite questionable above 1 kHz, and the presence of uneven beams can skew the evaluation of discrete reflections or echoes.

The equipment problems are, however, not insurmountable. Our proposal here is that portable impulsive sound generators can be used instead of the aforementioned equipment without compromising the accuracy of the results. Regarding sound generators, instead of a large dodecahedron loudspeaker, it is possible to use truly impulsive sound sources created by simple tools such as blank pistols, firecrackers and bursting air balloons. However, as many open-air rock art areas are protected natural landscapes, blank pistols and firecrackers may not be permitted due to the risk of causing fires. As this was our case, for our tests we chose air balloons. In addition to not being subject to any legal restrictions, our decision was guided by the results of a recent study, which revealed that air balloons with large diameters and sufficient air pressure produce sound impulses with good omnidirectionality, repeatability and a reasonably flat frequency spectrum (Pätynen et al., 2011). It has been also demonstrated that air balloons provide effective results in the analysis of other acoustic parameters, such as reverberation time, apparent source width and listener envelopment, that can be performed in parallel to the analysis of the DOA of sound reflections (Fausti and Farina, 2000; Jambrosic et al., 2008). In order to ensure that our experiments were repeatable and also that the results would be comparable with each other, we decided to inflate our air balloons to a diameter of 40 cm.

4.2. Sound recorder and spherical camera

Receivers do not usually have the size and weight problems associated with sound sources, but are still a type of equipment fundamental to the success of the acoustic experiments. In order to apply the Ambisonics technique to the study of the DOA of sound reflections in rock art landscapes, a series of decisions had to be taken regarding the type of microphone to be used. We considered several alternatives, including the use of spherical microphone arrays with larger number of microphones with the 3DVMS method used by one of us in previous research (Farina and Tronchin, 2013), but the problems associated with carrying weight in rock art research already commented above made us to discard this possibility. After careful consideration, we decided to use the Brahma™ A-format tetrahedral microphone as we identified as the most suitable for the fieldwork conditions common in rock art landscapes. This is because of its compactness, great portability and cost-effectiveness (www.aidasrl.it/brahma.html, www, ny-a). The Brahma™ microphone array had already been tested in 2011 with excellent results in enclosed areas (Farina and Tronchin, 2013) and, with some changes, in underwater spaces (Farina et al., 2012). The Brahma™ microphone consists of 4 cardioid capsules located at the vertex of a tetrahedron (Fig. 1).

The Brahma™ microphone probe, connected to a modified Zoom H2 digital recorder, records raw A-format signals, which are later digitally converted to B-format in the post-processing phase. The B-format signal is a four-channel stream containing the signals from 4 virtual microphones: one omnidirectional, which records the sound pressure (p), and three with a polar pattern called a "figure of eight", oriented along the three Cartesian axes, X, Y, Z. These three virtual microphones capture signals proportional to the Cartesian components of the sound particle velocity (v). Knowing p and the three components of v makes it possible to display the three-dimensional DOA of sound reflections in the post-processing phase. In 2008, the Brahma™ microphone was characterized by means of a number of anechoic IR measurements by Enrico Armelloni and Fons Adriaensen in the Sala Bianca at Casa del Suono in Parma. The purpose of this characterization was to create a set of FIR filters to perform the A to B-format conversion (http://pcfarina.eng.unipr.it/Public/Brahma/Brahma/). The computation of the 4 × 4 FIR filter matrix followed the processing method described in (Farina et al., 2010).

During our fieldwork the microphone was connected to a modified Zoom H2 digital sound recorder (Fig. 2). This recorder, which is able to supply 5 V of plug-in power to the microphones, operates at 48 kHz and 24 bits, 4 channels. It records standard uncompressed WAV files over a 16-GB secure digital (SD) card, which can be easily downloaded later to a computer. Two of the most interesting features of this device in terms of acoustic research in rock art landscapes are its low weight (110 g) and long battery life. In addition, this recorder offers the possibility of adjusting the microphone gain level through a fixed-gain selector, so the recordings are amplitude-calibrated.

A panoramic digital camera was added to the equipment described above (Fig. 3). This camera takes pictures that are essential for the dynamic plot of the sound reflections. For our tests we used a Ricoh Theta M15 Spherical Digital Camera, remotely controlled by an Apple iPad mini using the custom application provided by Ricoh. This camera is able to shoot full 360° × 180° spherical panoramas (photospheres) with a resolution of 6.4 megapixels in a single shot with almost no stitching errors. It is also extremely portable (weight 125 g and size 130 × 44 × 223 mm), which, as in the case of all the equipment described so far, is well adapted to research in rock art landscapes. An alternative to this camera, and some of the post-processing of data described in 4.4, would have been to use an acoustic camera but its extremely high cost made us disregard it.

Rock art landscapes are uneven, as rock art sites are typically shelters in cliffs located in mountains and gorges. The difficulty of moving in these landscapes led to our decision of investigating stationary echolocation, i.e. testing echoes from the place in the target – the section of the landscape where the cliff with the potential rock art shelters can be seen – but at a distance short enough to allow echoes to be heard. This meant that the distance to the shelters had to be chosen ad hoc and ranged from 22 to 36 m in the case of Baume Brune to 77–300 m in the Valle d'Ividoro. Tests points kept distances similar to each other.

4.3. Impulse response measurement

The Impulse Response (IR) is a measurement of the sound propagation from a sound source to a receiver device. In our fieldwork at Baume Brune and Valle d'Ividoro, IR measurements were made in the area adjacent to rock art sites, at a distance greater than 17 m from the reflecting surfaces. This is the minimum distance at which, in optimal atmospheric conditions, a sound reflection can be heard as a distinct echo by the human auditory system, as it corresponds to a time delay of 100 ms (Everest and Pohlmann, 2009: 61–63, Rossing, 2007: 388, Fig. 11.2).

In our tests, the recording device was set on a tripod (Fig. 2). The X-axis of the Brahma™ microphone was oriented towards the reflecting surface without selecting a specific target. The microphone capsules were positioned at a height of 1.6 m above the ground to simulate a listening position comparable to the average height of the human auditory system. As explained above, the sound source consisted of sound impulses created by bursting 40-cm diameter air balloons. A team member, holding the balloon

Fig. 2. The modified Zoom H2 digital recorder connected to the Brahma™ microphone during the Impulse Response (IR) measurement in the adjacent area of the shelter S8 at Baume Brune.

Fig. 3. The Ricoh Theta M15 spherical digital camera mounted on the tripod during the field work.

above their head in order to avoid possible acoustical obstruction in the measurement field, burst it by sticking a pin into its lower part. The balloons were burst in different positions around the microphone, always at the same distance from it (2 m) and with the

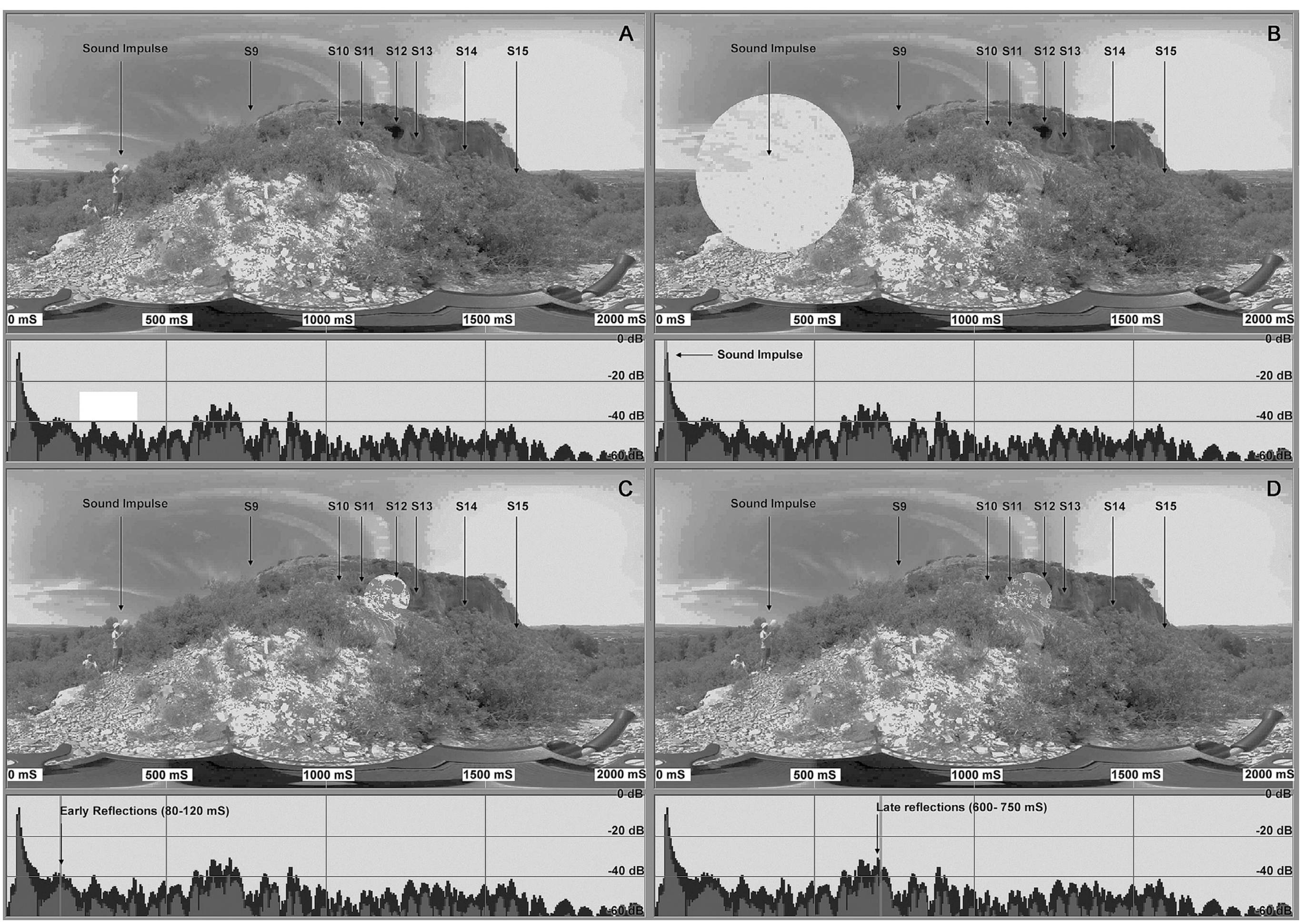

Fig. 4. Four frames of the slow motion video of the DOA of sound reflections at Baume Brune. The spherical photo of the upper part of each frame is complemented in the lower half of each frame by a graphical representation of the variation in sound intensity (I) and energy ratio (r_E) of sounds. A – before the sound impulse, B – direct sound waves created by the sound impulse, C – early reflections (80–120 ms), perceived as reverberation, arriving from Shelters S11 and S12 (which are the only shelters with rock art depictions), and circles representing the DOA of sound reflections, D – late reflections (600–750 ms), perceived as echoes, arriving from the same location.

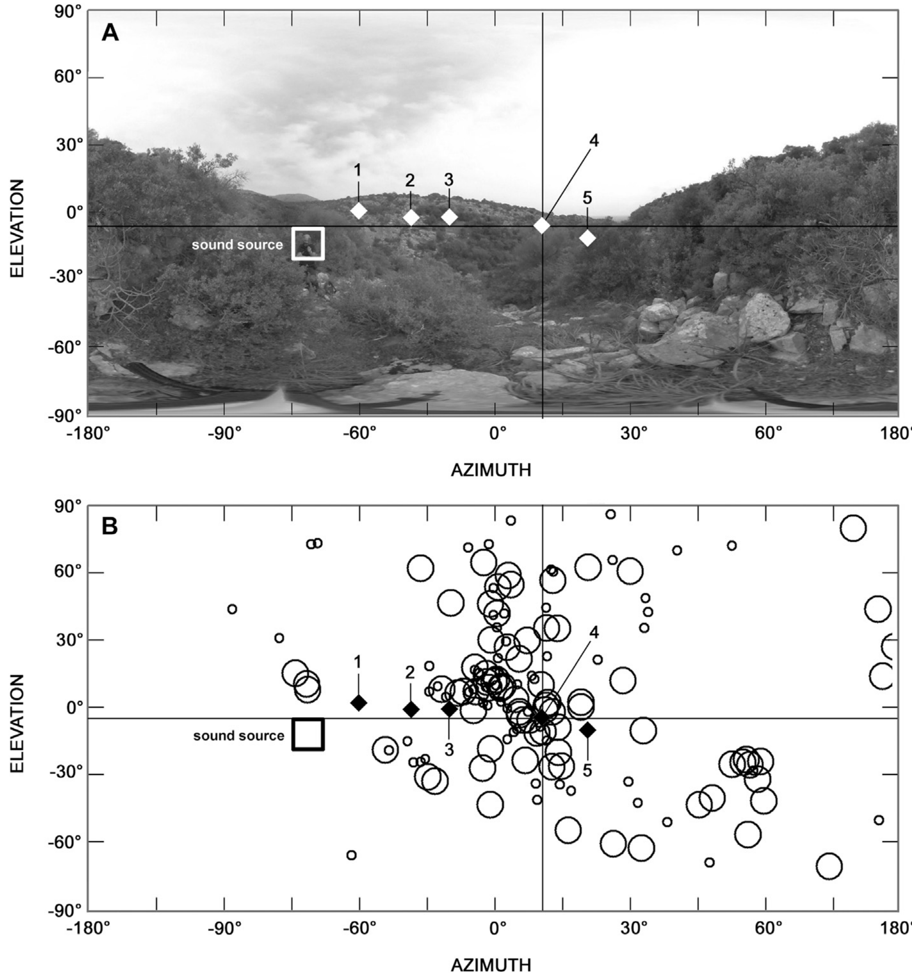

Fig. 5. IR measurement in Valle d'Ividoro. A – Spherical photo of test point 3 with the localization of the sound source (square) and Shelters 1 to 5 (only Shelters 3 and 4, the latter known as Grotta Pazienza, have rock art); B – Bubble chart representing the azimuth, elevation and intensity of the DOA (large circles represent sound reflections with an intensity of −3 dB than the original sound; small circles sound reflections with an intensity of −4 dB than the original sound). For the small motion video of the DOA of sound reflections see supplementary material.

microphone at the same height above the ground (1.6 m). Every IR measurement session consisted of three balloon bursts in order to create a consistent dataset. After each IR measurement session, the recording device was removed from the tripod and replaced with the Ricoh Theta M15 spherical camera. The frontal lens of the optical camera was oriented towards the same direction as the X-axis of the microphone and it was placed at the same height above the ground. A panoramic picture was taken using the camera remote control on the iPad.

4.4. Post-processing and analysis

The post-processing and analysis of IR measurements is articulated in three phases. First, the raw capsule signals (A-format) recorded by the Brahma™ microphone during IR measurement sessions are downloaded to the computer and converted by the BramaVolver software into B-format (Farina et al., 2007; www, ny-b). This conversion is carried out by the software by applying the specific matrix of FIR filters computed for this microphone probe, as described in section 3.2.

The second phase consists of calculating the precise azimuth, elevation and intensity of sound reflections from the B-format signals. These values are obtained by a Visual Basic program named "IR-Spatial" (www, ny-c) from the B-format signals by applying the equations described in Farina and Ugolotti (1999) and Farina and Tronchin (2013). In particular, IR-Spatial produces two outputs. The first output is a text file containing the values of the three Cartesian components of sound intensity (I_X, I_Y, I_Z) and the total energy ratio ($r_E = |I|/D \cdot c$, where r_E stands for the instantaneous value of the energy ratio, I for the sound intensity, D for energy density, and c for the speed of sound) both expressed as a function of time by slicing the IR in a sequence of partially-overlapped time slots with an adjustable duration (i.e. 2 ms). From the three components of the sound intensity (I_X, I_Y, I_Z) it is possible to calculate the value of the azimuth and elevation of each impinging wavefront (Farina and Tronchin, 2013: Eq. 6). The total energy ratio value (r_E) describes the diffuseness of the sound field, ranging from between 0 (complete diffusion, so there is no real directional information associated with the time slot) and 1 (plane progressive wave, indicating that the acoustical energy is travelling in just one, well-determined direction). It gives a simple description of the nature of the sound field (active or reactive).

In phase 2 the second output of the IR-spatial program is a slow-motion video (see supplementary material) of the impulse response by which it is possible to "see" where the echoes and reverberations are coming from. This animation provides the user with a visualization of the DOA of sound reflections. This is similar to the so-called "acoustic camera" (Heilmann et al., 2014; Manrique

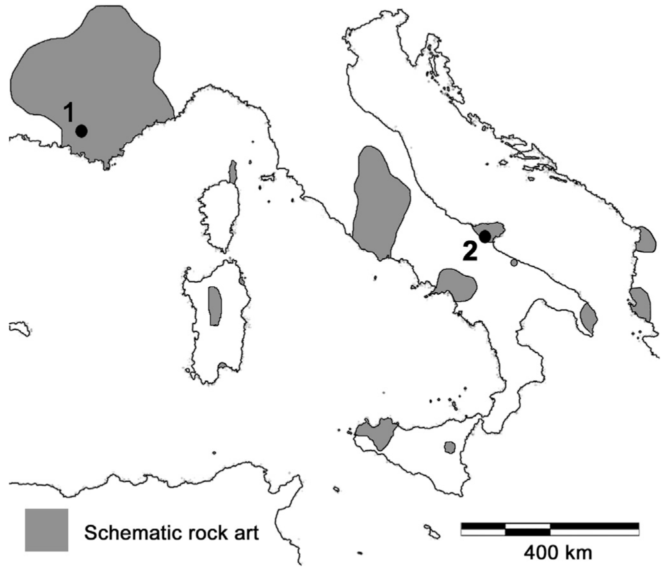

Fig. 6. Map of the Central Mediterranean showing in shading the area where Schematic art is found. 1. Baume Brune. 2. Valle d'Ividoro.

Ortiza et al., 2015). The audible sound reflections are charted in time steps of a few milliseconds as moving circles over the original spherical photo taken from the microphone position and stretched as a rectangular image using the equirectangular projection (Fig. 4). The circle, representing the DOA (azimuth and elevation) and diffusion of each audible reflected sound, has a diameter proportional to the magnitude of the sound intensity vector (I) and a degree of opaqueness proportional to the value of the energy ratio (r_E) (Fig. 5).

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.jas.2017.04.008.

The third phase in the post-processing data aims to establish the statistical correspondence between the DOA of sound reflections and the location of decorated sites. For this the azimuth, elevation and diffuseness of the DOA of sound reflections obtained in the second phase of the analysis is compared to the location of decorated rock shelters. This correspondence is evaluated for each IR test by calculating the root-mean-square error (RMSE) between the DOA of each audible echo and reverberation and the geographical location of rock art shelters. If low RMSE values are found in consecutive tests, we can assume that an individual standing in the different places where the IR measurements were carried out would feel that the sound reflections were coming from decorated rock shelters. This also means that there is a high probability of echolocation having been used to select the shelters to decorate.

5. Discussion of the results obtained in the Baume Brune and Valle d'Ividoro rock art landscapes

During two fieldwork seasons in 2015 and 2016 we applied the

Fig. 7. Baume Brune. A. Panoramic view of the Baume Brune cliff showing the locations of the rock art shelters. Photo by the authors. B. Aerial photograph of the Baume Brune cliff showing the test points and rock art shelters. Photo courtesy of the French IGN.

new measurement technique explained above for the three-dimensional characterization of echoes and reverberation in two Central Mediterranean rock art landscapes, those of Baume Brune (Vaucluse Department, France) and Valle d'Ividoro (Puglia, Italy) (Fig. 6). Both are characterized by having Schematic art which scholars date to the Neolithic (Gravina and Mattioli, 2009; Hameau, 2002: 55–68). In both areas only a few shelters (18% of the total in Baume Brune and 27% in Valle d'Ividoro) have rock art and there is no apparent difference regarding erosion in all the others to think that there are other reasons for which they were not selected. This means that rock art artists made a choice regarding the shelters that were suitable to contain paintings. The acoustic tests undertaken at these two rock art landscapes aimed to investigate whether echolocation may have been the method, or perhaps one of the methods, that guided the artists in their selection.

Baume Brune is a one-km-long cliff oriented E-W with 43 natural shelters, of which only 8 were selected to be painted (Fig. 7). In previous publications it was noted that other criteria that may have influenced the selection of the shelters were their dominant position, southern orientation, the red colour of walls and the special humidity of the area (Hameau, 2002). However, all these criteria apply for all the shelters along the cliff line whereas, as said, only a selection of eight were decorated, the geology being apparently equal to all of them. A total of 10 tests were made keeping a regular distance of about 80 m between each test location. The tests were carried out at a distance of 22–36 m away from the cliff. Earlier in the article we included Fig. 4 displaying four frames of the slow-motion video with the IR-measurements of Test Number 3. The figure clearly illustrates the early and late reflections that come from the only rock cavities with rock art in that section of the cliff (Shelters 9–15). Table 2 and Fig. 9 show how the results of the tests made in front of the rock art sites obtained values with low RMSE. The best results were obtained in Shelters 12 and 32. Baume Brune 12 is the cavity after which the whole cliff is named. It has the highest number of figures and is the only shelter with black paintings. In Baume Brune 32 there is an arboriform representation. It is noteworthy that on the eastern part of the cliff there is a sequence of five cavities (Fig. 8) that are very similar to each other in terms of their shape. However, only Baume Brune 32 has paintings and this coincides with lower RMSE values. This means that an echolocator surveying the area would hear the echoes and reverberations coming from that shelter in the cliff.

Table 2
RMSE values obtained at Baume Brune. T means tests; RA motifs correspond to the number of rock art motifs in each shelter; Az Azimuth; El Elevation; DS Distance from the test point to the shelter.

Shelter	RA motifs	T1			T2			T3			T4			T5		
		Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds
S1	5	59	23	26 m	56	27	69 m	–	–	–	–	–	–	–	–	–
S2	1	57	28	23 m	50	28	56 m	–	–	–	–	–	–	–	–	–
S3	2	41	24	23 m	48	27	46 m	–	–	–	–	–	–	–	–	–
S4	4	48	26	23 m	58	27	40 m	–	–	–	–	–	–	–	–	–
S5	–	40	22	39 m	64	29	22 m	70	21	58 m	–	–	–	–	–	–
S6	–	–	–	–	61	25	23 m	84	22	56 m	–	–	–	–	–	–
S7	–	–	–	–	63	24	23 m	76	30	44 m	–	–	–	–	–	–
S8	–	–	–	–	69	22	19 m	60	34	41 m	–	–	–	–	–	–
S9	–	–	–	–	65	21	38 m	57	28	27 m	–	–	–	–	–	–
S10	–	–	–	–	40	23	44 m	55	25	28 m	–	–	–	–	–	–
S11	–	–	–	–	39	24	49 m	35	21	30 m	–	–	–	–	–	–
S12	9	–	–	–	38	22	55 m	32	26	32 m	–	–	–	–	–	–
S13	–	–	–	–	40	21	59 m	41	29	25 m	–	–	–	–	–	–
S14	–	–	–	–	–	–	–	54	24	34 m	–	–	–	–	–	–
S15	–	–	–	–	–	–	–	56	22	37 m	–	–	–	–	–	–
S16	–	–	–	–	–	–	–	–	–	–	68	22	34 m	–	–	–
S17	–	–	–	–	–	–	–	–	–	–	68	22	44 m	–	–	–
S18	–	–	–	–	–	–	–	–	–	–	70	24	52 m	–	–	–
S19	–	–	–	–	–	–	–	–	–	–	–	–	–	65	28	36 m
S20	–	–	–	–	–	–	–	–	–	–	–	–	–	69	24	27 m
S21	–	–	–	–	–	–	–	–	–	–	–	–	–	68	30	31 m
Shelter	RA motifs	T6			T7			T8			T9			T10		
		Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds
S22	–	70	32	27 m	–	–	–	–	–	–	–	–	–	–	–	–
S23	6	56	32	21 m	–	–	–	–	–	–	–	–	–	–	–	–
S24	1	52	28	23 m	–	–	–	–	–	–	–	–	–	–	–	–
S25	–	–	–	–	69	34	31 m	–	–	–	–	–	–	–	–	–
S26	–	–	–	–	67	36	30 m	–	–	–	–	–	–	–	–	–
S27	–	–	–	–	–	–	–	71	38	37 m	52	35	55 m	–	–	–
S28*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
S29	–	–	–	–	–	–	–	69	32	36 m	56	28	56 m	–	–	–
S30	–	–	–	–	–	–	–	65	34	51 m	54	29	45 m	–	–	–
S31	–	–	–	–	–	–	–	49	32	52 m	43	30	40 m	–	–	–
S32	2	–	–	–	–	–	–	28	28	54 m	32	31	36 m	–	–	–
S33	–	–	–	–	–	–	–	34	30	60 m	30	24	33 m	–	–	–
S34	–	–	–	–	–	–	–	–	–	–	39	29	33 m	–	–	–
S35	–	–	–	–	–	–	–	–	–	–	41	30	37 m	–	–	–
S36	–	–	–	–	–	–	–	–	–	–	66	31	58 m	–	–	–
S37	–	–	–	–	–	–	–	–	–	–	65	32	64 m	–	–	–
S38	–	–	–	–	–	–	–	–	–	–	–	–	–	71	28	27 m
S39	–	–	–	–	–	–	–	–	–	–	–	–	–	70	29	27 m
S40	–	–	–	–	–	–	–	–	–	–	–	–	–	73	28	28 m
S41	–	–	–	–	–	–	–	–	–	–	–	–	–	69	29	29 m
S42	–	–	–	–	–	–	–	–	–	–	–	–	–	65	30	26 m
S43	–	–	–	–	–	–	–	–	–	–	–	–	–	70	31	25 m

* in S28 indicates that it was not possible to analyze this shelter because it was out-of-sight and hidden inside a narrow canyon along the rocky cliff.

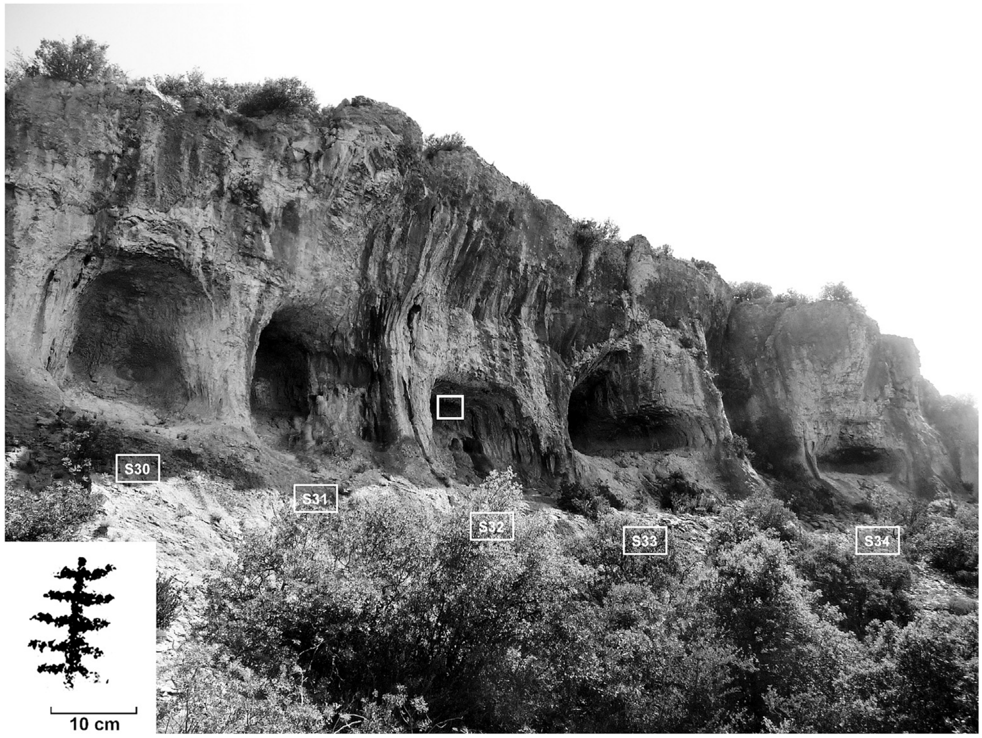

Fig. 8. Shelters 30 to 34 on the eastern side of Baume Brune. Only Shelter 32 has rock art (arboriform). Photo by the authors.

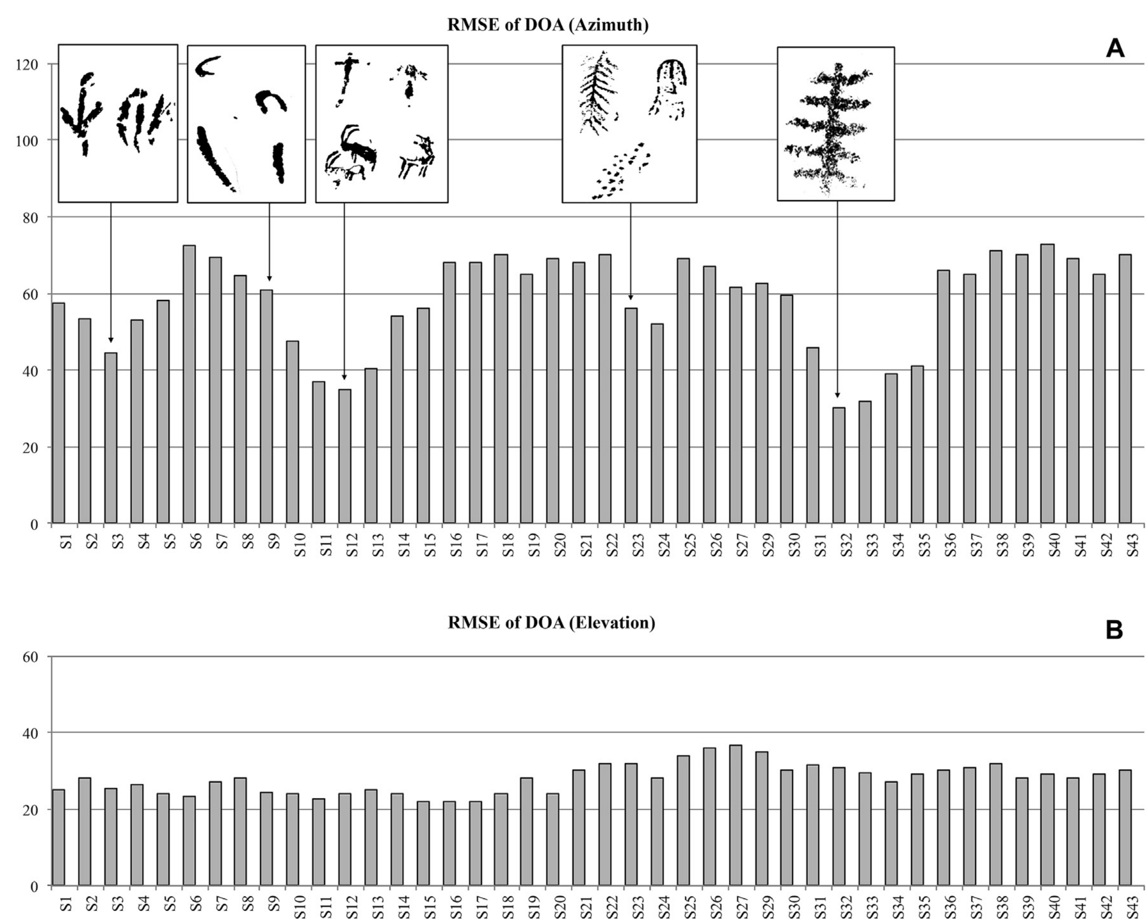

Fig. 9. Bar charts of the RMSE of the DOA of sound reflections at Baume Brune. Values for A. azimuth; B. elevation. A sample of rock art motifs in Shelters 1–4, 9, 12, 23 and 32 is displayed.

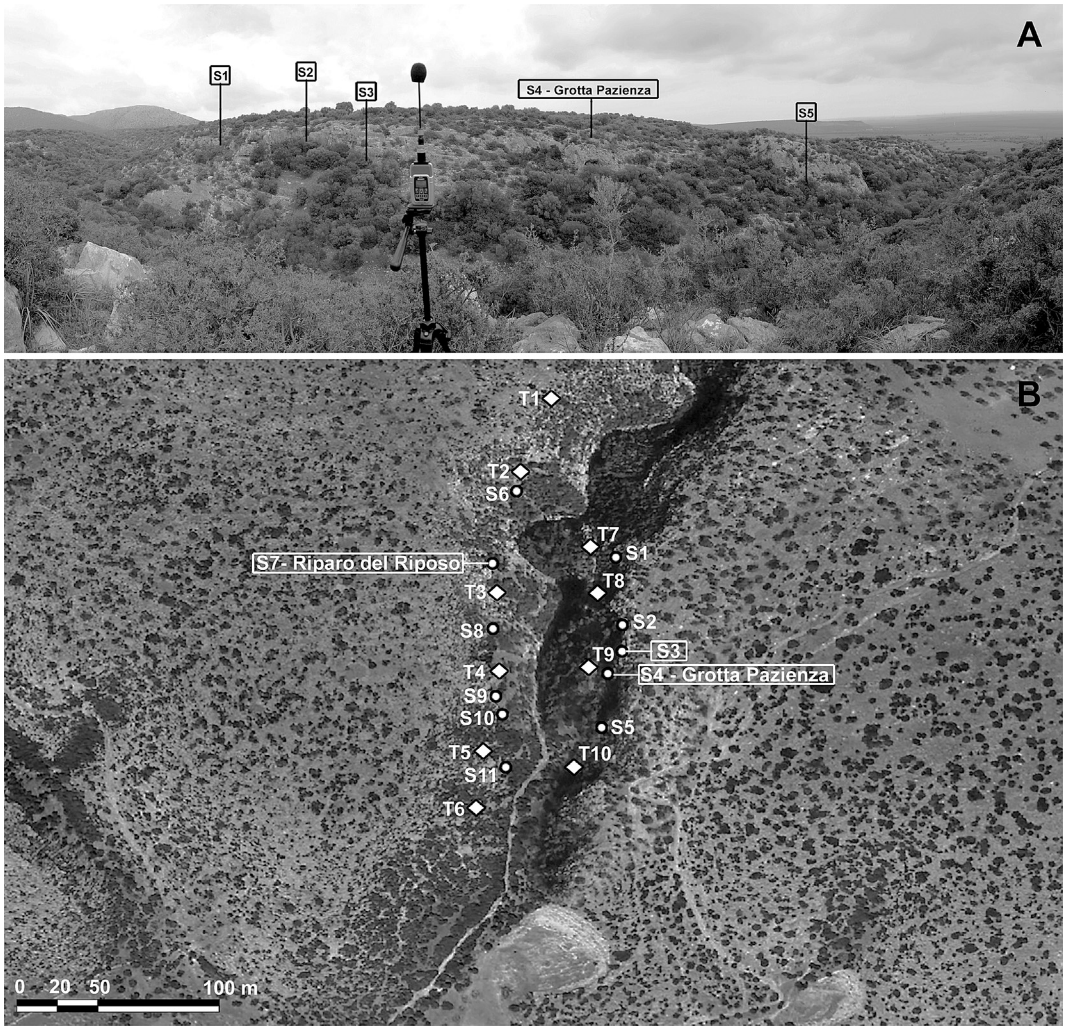

Fig. 10. Valle d'Ividoro. Panoramic view. A. Panoramic view of the eastern side showing the locations of all the shelters (only Shelters 3 and 4 have paintings). Photo by the authors. B. Aerial photograph of the Valle d'Ividoro gorge showing the test points and shelters. The rock art sites are indicated. Photo courtesy of Geoportale Nazionale, Ministero dell'Ambiente e della Tutela del Territorio e del Mare.

Table 3
RMSE values obtained at Valle d'Ividoro. A. Eastern side of the cliff. B. Western side of the cliff. For abbreviations see Table 2.

Shelter	RA motifs	T1			T2			T3			T4			T5			T6		
		Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds
S1	–	98	38	130 m	96	43	120 m	82	41	88 m	108	51	123 m	61	32	174 m	113	50	230 m
S2	–	75	34	166 m	102	48	158 m	74	36	82 m	101	48	98 m	54	34	150 m	110	50	198 m
S3	3	70	36	187 m	85	42	173 m	64	36	82 m	96	49	86 m	47	33	136 m	107	50	179 m
S4	21	60	32	220 m	70	41	202 m	54	36	95 m	95	49	77 m	38	33	120 m	103	50	153 m
S5	–	120	36	301 m	90	40	262 m	56	38	145 m	106	50	102 m	46	31	108 m	102	54	104 m

Shelter	RA motifs	T7			T8			T9			T10		
		Az	El	Ds	Az	El	Ds	Az	El	Ds	Az	El	Ds
S6	–	79	36	76 m	82	50	110 m	98	41	157 m	108	49	211 m
S7	10	68	36	82 m	62	44	91 m	69	40	118 m	73	47	162 m
S8	–	75	43	108 m	77	51	89 m	85	38	86 m	97	38	122 m
S9	–	103	40	145 m	120	50	120 m	115	34	80 m	106	38	92 m
S10	–	94	38	157 m	86	50	127 m	96	38	81 m	104	38	82 m
S11	–	114	40	195 m	117	51	160 m	94	42	106 m	103	40	86 m

The rock art in the Valle d'Ividoro is located in a 3-km-long gorge in which it is concentrated in an 800-m section (Fig. 10). In this part of the valley there are 11 shelters, of which only 3 have paintings. The landscape in Valle d'Ividoro is much more difficult than that of Baume Brune as it has a very steep valley bottom and dense vegetation cover. This explains some of the decisions that had to be taken regarding the distance between tests (about 160 m) and from the cliff (between 77 and 300 m, depending on the test).

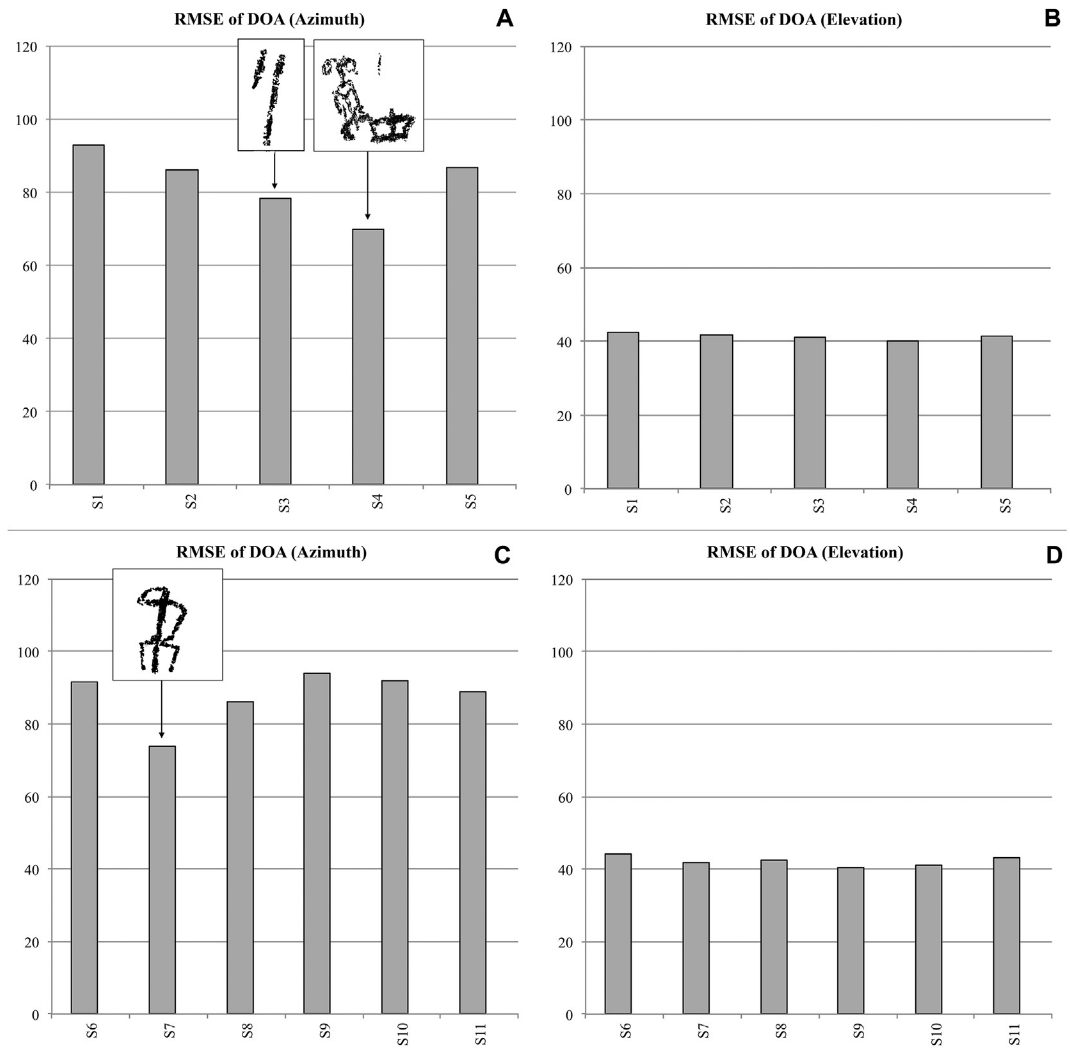

Fig. 11. Bar charts of the RMSE of the DOA of sound reflections at Valle d'Ividoro. A and B. Eastern side of the cliff. C and D. Western side of the cliff. A and C values for azimuth; B and D values for elevation. A sample of rock art motifs in Shelters 3, 4 (Grotta Pazienza) and 7 (Riparo del Riposo) is displayed.

Despite the differences in these distances in relation to Baume Brune, the method again showed its validity for testing echolocation. Table 3A and Fig. 11A-B show the results of the tests carried out on the eastern side of the cliff. The lesser RMSE again coincides with the rock shelter with the largest number of paintings, the Grotta Pazienza (Shelter 4). The special nature of this shelter can also be seen graphically in Fig. 5, which was used earlier in the article to demonstrate how the DOA of sound reflections can be represented visually. In the eastern part of the valley, Shelter 3, which also has some prehistoric paintings, had the second lowest RMSE values. Table 3B and Fig. 11C–D provide the results for the western side of the gorge and from the six possible shelters. The lowest RMSE corresponds to the Riparo del Riposo, the only one of those shelters with rock art.

6. Conclusion

The location of rock art sites in areas with special echoing properties is well known among certain hunter-gatherer and early agriculturalist societies around the world, although in Europe all memory about this practice disappeared a long time ago. This is why scientific methods developed in the field of acoustical physics are needed to attest to the likelihood of these practices. In this article the Ambisonics method has been proposed as the best one to assess experimentally the Direction of Arrival (DOA) of echoes, which is the way in which echolocators naturally identify the places where sound reflects in the landscape. This method has the advantage over the binaural technique of producing much more precise measurements of the DOA of echoes and reverberation and mapping reverberant sound tails. Furthermore the Ambisonics method, as we have applied it, has the benefit of using small size, highly portable equipment. This is a great improvement for rock art researchers as it is compatible with research in remote, open-air environments of the type in which many rock art landscapes are found. There may be, however, some areas of improvement, such as finding out a way to add movement to the testing, an issue that, as explained above, was discarded in our fieldwork because of the rough nature of the terrain.

The post-processing and analysis of the Impulse Response (IR) measurements of the sound propagation has been organized in several phases. We have worked with measurements in B-format and calculated the values for the azimuth, elevation and sound intensity of the sound reflections. This has allowed us to create a slow-motion video that has made it possible to "see" where the echoes and reverberations were coming from during our fieldwork. With the data thus obtained the correspondence between the DOA of sound reflections – the place where the echoes come from – and the location of decorated sites has been established.

In conclusion, the acoustic examination of the DOA of sound reflections at the Schematic rock art landscapes of Baume Brune in France and Valle d'Ividoro in Italy through the Ambisonics method indicate that the few shelters chosen to be painted were precisely those that echolocators would identify as having special acoustic properties. Therefore, we conclude that there is a strong probability of echolocation having been used as a method by Neolithic artists to select the shelters in which to produce rock art.

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