acoustics

Article

The Bacinete Main Shelter: A Prehistoric Theatre?

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Abstract: In the last few years, archaeoacoustic studies of rock art sites and landscapes have undergone significant growth as a result of renewed interest in the intangible aspects of the archaeological record. This article focuses on the acoustic study carried out in the rock art complex of Bacinete, Cádiz (Spain). After describing the archaeological site and its importance, a representative set of monaural and spatial IRs gathered onsite is thoroughly analysed to explore the hypothesis that the sonic component of the site played an important role in how prehistoric people interacted with it. Additionally, we briefly discuss the challenges of analysing the acoustics of open-air spaces following the recommendations of the ISO 3382-1 guidelines, a standard developed not for open-air spaces, but for room acoustics. The results obtained confirm the favourable acoustic conditions of the Bacinete main shelter for speech transmission. The different subjective acoustic impressions obtained in a somewhat similar shelter located nearby, Bacinete III, are also explained, alluding to a lesser degree of intimacy felt in the latter.

Keywords: archaeoacoustics; heritage acoustics; rock art; acoustic measurements

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1. Introduction

Beginning as long as forty thousand years ago, and probably even earlier in some places, people all over the world have marked the land with images, a cultural practice that has continued in some places up to our days. The archaeological study of this cultural manifestation has traditionally focused on analysing the style and chronology of the painted or carved motifs or on examining the places where the art is found. However, beginning timidly in the 1980s, and increasingly in the last two decades, there has been growing interest in the intangible aspects associated with rock art sites. In this respect, rock art studies are no different from other fields of archaeology. New theoretical and methodological approaches have led to the appearance of subdisciplines in archaeology, among them archaeoacoustics, which studies the role of sound in past cultures. This field of study brings together knowledge not only from archaeology but also from fields such as architectural acoustics, anthropology and musicology. Archaeoacoustics aims to investigate how past societies perceived and interpreted different types of sound experiences in the context of their cultural practices [1]. From early studies assessing reverberation and echoes measured using simple methods in Palaeolithic caves [2–5] and at post-Palaeolithic rock art sites [6,7], the field has moved on to use more sophisticated methods.

In the last few years, the technological development of acoustic measurement instruments and software for audio processing has allowed a new generation of researchers to expand the studies on the archaeoacoustics of rock art sites and landscapes. This can be illustrated by recent work undertaken by several teams. One of them is that of Riitta Rainio and colleagues, who have been examining acoustic phenomena recorded at Finnish post-Palaeolithic painted sites with impulsive sound sources and binaural recording techniques [8,9]. In these areas, the researchers have identified the presence of echoes and observed that the cliffs chosen as a medium for the images act as potent sound reflectors [9]. Another team was that formed in the context of the Song of the Caves project. A group of experts, including Rupert Till and Bruno Fazenda, analysed the relationship between the location of the rock art and the acoustic properties of five Palaeolithic caves [10,11]. After an exhaustive statistical study, the authors found a subtle—although sufficiently significant—correlation between the acoustics of the spaces and the location of the art. Moreover, since 2012, a team led by Margarita Díaz-Andreu has been carrying out archaeoacoustic research at post-Palaeolithic sites on several continents [12–16]. Based on audio recordings, the registration of site impulse responses (IRs) and the analysis of a wide set of acoustic parameters, the results obtained by this team suggest there was a frequent relationship between the presence of graphic representations and the acoustic properties of rock art sites in many areas of the world. In this respect, it has been argued that places with particular acoustics, such as the Cueva Pintada area in Baja California and the site of Cuevas de la Araña in Spain, may have been chosen to increase the sensorial impact of the social or ritual activities performed in the shelters. Thus, acoustic effects, such as echoes or reverberation, would have intensified sound perception in them. The importance of sound experiences and acoustics at rock art sites has also been corroborated by this team thanks to the presence of musical instruments in some caves and open-air shelters with paintings [17,18] and the depiction of dances in several decorated shelters [19].

The methods followed by all these groups have evolved over time. This is well illustrated by the work of Díaz-Andreu, Lazarich and others in the area of Cádiz and by comparing this article with another published almost a decade ago [20]. The fieldwork for that investigation was undertaken in 2012. It attempted to answer the question of whether the acoustic properties of the Bacinete rock art complex—one of the most emblematic decorated sites in the south of the Iberian Peninsula—could have influenced the activities related to the production and use of images. More specifically, the aim of the research was to test the hypothesis—defended by some rock art experts—that the main shelter of this complex could have functioned as an "auditorium" [20] (p.11), [21] (p. 510). The acoustic tests performed at the time were based on human-made sounds, such as voices, whistles and hand clapping, and indicated the presence of reverberation. However, would their conclusions stand up to measuring the acoustics with a more accurate methodology? This question led us to carry out a new fieldwork campaign in June 2021.

This article, after briefly describing the archaeological site of the Bacinete rock art complex, offers an explanation of the acoustic measurements used to capture monaural and spatial IRs undertaken in the core rock art area of the complex. Before that, we discuss the challenges of analysing the acoustics of open-air spaces following the requirements and specifications of the ISO 3382-1 guidelines, a standard developed not for open-air spaces, but for room acoustics. The acoustic data gathered onsite is then thoroughly analysed to explore the hypothesis that the sonic component of the Bacinete main shelter and Bacinete III played an important role in how prehistoric people interacted with it. Moreover, the results of this research contribute to a better understanding of the activities that could have been carried out at rock art sites and the sociocultural practices of prehistoric societies.

2. The Bacinete Rock Art: An Archaeological Approach

The Bacinete rock art complex is located in the Niño mountain range, in the southeast of the province of Cádiz, Spain. Rock art was produced in this region over millennia, from the Upper Palaeolithic [22,23] to the Late Middle Ages [24]. The site is close to the so-called Bacinete mountain pass at an altitude of 180 m in the Palmones river basin and not far from the sea. The shelters are in an area in which visibility of the surroundings is limited. The only exception is one shelter located at a distance from the others, Shelter I, which has extensive views across the landscape to Algeciras Bay and the Rock of Gibraltar [21] (pp. 494, 499). The site is easily accessed and one of the remarkable features of the area is the spectacular geological rock formations of aljibe sandstone in which the painted shelters are inserted [21] (p. 492). This type of rock is prone to wind erosion and its effects on the sandstone panels are evident. That, and the influence of water and other factors, has resulted in the fading of the paintings and even the possible disappearance of some of them.

The Bacinete rock art has been known for about a century. It was first published in 1929 by Henri Breuil [25] (63–67, Plates 26, 27, 31) and later by many other researchers [21,26–29] (for a historiographical overview, see [21] (pp. 495–497)). Ten different sites have been identified at the complex in an area of some 250 by 150 square metres. Five sites, however, are concentrated in a smaller area of c. 60 by 45 square metres, which will be designated in this article as the core rock art area of the Bacinete complex (Figure 1). The sites in the core area are the main shelter, about which more is said below, and another four that are designated with Roman numerals as Bacinete III, IV, V and VIII. Rock art experts have identified 169/171 motifs for the main site (see below), three sites with 22, 37 and 17 motifs, respectively, and one site with a single motif [29] (pp. 68, 106–130). Whereas all sites have Schematic paintings, exclusively in the main shelter there are some figures produced in the earlier Laguna de la Janda style, also known as the semi-naturalistic style.

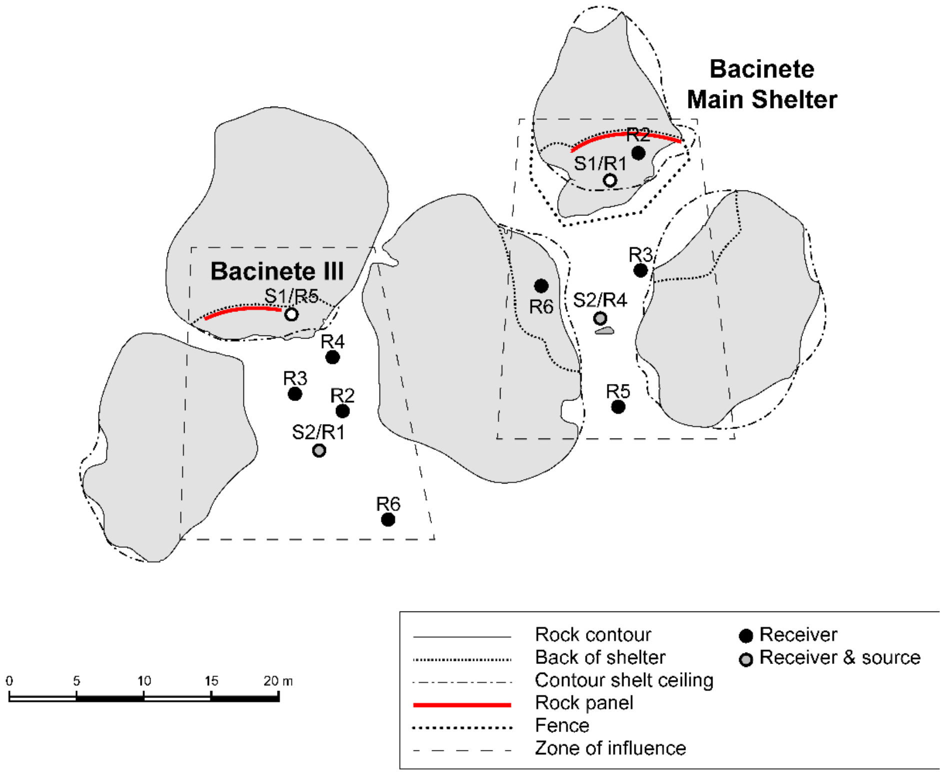


Figure 1. Location of Bacinete main shelter and the Bacinete III shelter in the core rock art area. The approximate sound source (S) and receiver (R) positions set for registering impulse responses are shown. Source: Prepared by the authors based on Lazarich et al. [21] (Figure 5).

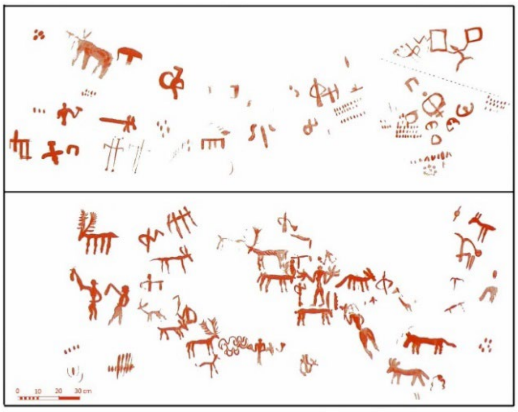
2.1. The Main Shelter

In the core rock area of the Bacinete complex, one of its shelters, known as the large or main shelter (Figure 2), stands out for its large number of motifs, styles and production phases, as well as the particular spatial configuration of the rock formations in front of the shelter.

Figure 2. General view of Bacinete main shelter. The red frame indicates the location of the rock art panels. Photographs by N. Santos da Rosa, Artsoundscapes project, 2021.

The number of motifs is severalfold greater than that identified in any of the other shelters, not only in the core area but in the whole complex [29] (p. 68). There is a slight disagreement with respect to the total number of figures, 171 [30] (p. 503) or 169 [29] (p. 68). This minor divergence is probably due to the difficulties associated with working out the nature of certain motifs, given the poor preservation of some of them.

The second reason the main shelter stands out is that the motifs painted in it belong to two distinct styles or rock art traditions: an earlier Laguna de la Janda style, also called semi-naturalist style, and the Schematic style (Figure 3). The Laguna de la Janda style owes its name to the location of what was one of the largest wetlands on the southern Iberian Peninsula until it was drained in the late 1960s [30] (pp. 189–191), [31] (p. 389). In terms of chronology, Solís argues that the earlier style may have originated with the last hunter-gatherer populations in the area and continued after the adoption of agriculture and husbandry [29] (p. 34), the latter being the appropriate date for Lazarich et al. [20] (p. 6), [21]. Regarding the Schematic style, superimpositions make it clear that it is later in time, and both teams date it to the Neolithic and Chalcolithic periods [29] (pp. 45, 150). In addition to a large number of figures and the two distinctive styles, the main shelter is different from all others in the complex because its paintings were produced in at least five different periods. The earliest motifs represent people and animals (principally cervids) that have been classified as Laguna de la Janda style. More motifs were painted later, albeit with a higher degree of schematism. The trend towards schematism is even more marked in the third period, when other motif types, such as dots and different animal species, including canids, were added. More signs possibly symbolising anthropomorphs, as well as dots, were inserted in a fourth phase, and this was followed by a final moment in which the anthropomorphs, zoomorphs (all very schematic) and signs were painted on the surface of the shelter's ceiling and not on the rear wall [29] (pp. 145–146). Spatially, the motifs of the main shelter are located in an area of several metres in which two sectors have been identified. The first comprises the entire rear wall of the shelter, where 13 panels have been distinguished. Sector 2, with only one panel, is on the ceiling and corresponds, as mentioned above, to the most recent painting phase [29] (pp. 106–130).



(**a**) (**b**)

Figure 3. (**a**) State of conservation of some of the motifs painted in the main shelter of Bacinete with scales added (photograph by M. Díaz-Andreu, Artsoundscapes Project, 2021); and (**b**) record of some of the scenes in the main shelter by Breuil [25] (Plate XXVII).

The final characteristic that distinguishes the main shelter from all the others in the Bacinete complex, with the partial exception of Bacinete III (see below), is its spatial configuration. As explained in the introduction, the site has previously been described as an "auditorium" or a "natural amphitheatre", where the main shelter is considered to be the "stage". Lazarich's team even mentions the visual resemblance of the rock shelter where the panel is to an "acoustic shell". The main shelter is a south-facing concave surface 9.6 m wide by 2.9 m high and 3.10 m deep in which the floor slopes slightly towards the exterior [21] (Figure 2). In front of the painted shelter there is an enclosed flat area surrounded by large rock outcrops (some of them hosting other shelters that are also decorated, Figure 1). This area loosely resembles the "stalls" for "spectators "characteristic of an Italian-style opera house. The area has room for a medium-sized group of people to watch what is taking place at the main shelter. If we calculate about four people per square metre [32] (p. 345), we can estimate a maximum "audience" of some 40 to 50 people. Furthermore, two possible elevated theatre "boxes" (*palcos*) in the rocky outcrops in front of the main shelter are mentioned [21] (p. 510).

Based on all the above, Lazarich et al. and Solís argue that the site could have been used as a gathering place for symbolic or ritual practices [21] (p. 511), [29] (pp. 151, 154), although Bacinete itself cannot be considered as an aggregation site. The archaeological evidence does not indicate that this is a settlement zone, despite the fact that in the area around the rock art complex some flint and sandstone tools (fragments of blades and denticulated blades or sickle teeth) have been found [21] (pp. 512–513), [29] (p. 44). Despite being more restricted in their movements across the landscape in comparison to the previous hunter-gatherer societies, communities with a sedentary way of life also moved around, sometimes as a whole, as happens today in the Catholic "romerías", annual religious pilgrimages to chapels and shrines connected with a particular saint. Events in which the entire populations of villages walk to sanctuaries located in mountainous areas have been known since prehistory on the Iberian Peninsula [33,34]. Moreover, mountain passes are considered special places by many traditional societies (see, for example, [15]).

2.2. Bacinete III

Although there are differences, such as the types and much lower numbers of motifs—only 22, an anthropomorph, dots and a series of unidentified figures—and no evidence of distinct styles and phases [21] (pp. 499–500), [29], the raised platform of the floor of Bacinete III (Figure 4) and the flat area in front of it indicate some interesting similarities with our initial study object, the main shelter. For this reason, it was decided to also acoustically test it. The Bacinete III shelter is 8.3 m long, 3.8 m high and 2.8 m deep. The crowd that would have been able to fit in front of the shelter would also have been similar in size, perhaps a little larger, than at the main shelter. Intriguingly, no author has raised the possibility of it being used as a performance area.

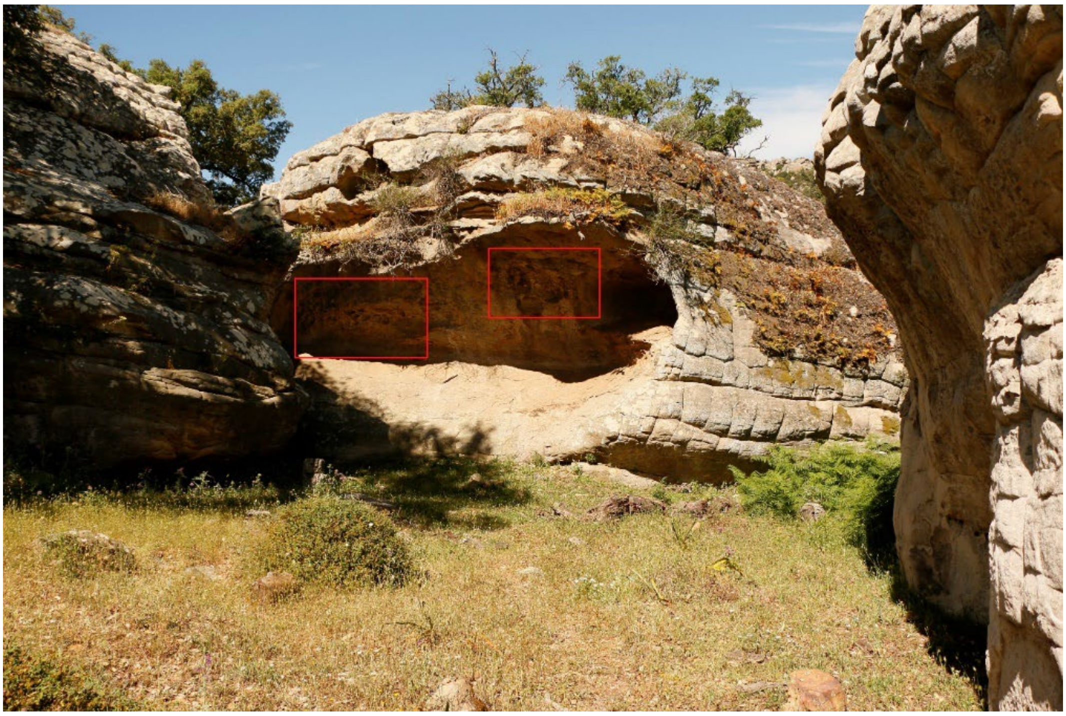


Figure 4. General views of Bacinete III. The location of the rock art panels is framed in red. Photograph by N. Santos da Rosa, Artsoundscapes Project, 2021.

3. Materials and Methods

3.1. Assessing the Acoustics of Open-Air Spaces with ISO 3382-1

Despite referring to indoor performance spaces, numerous studies have successfully adopted ISO 3382-1 [35] as a reference when investigating the acoustic field in open-air spaces, including those from prehistory to our days, even though their sound field differs considerably from the ideal diffuse field considered in the standard [36–44]. In this respect, ancient theatres represent one of the most studied groups of open-air historical sites (see, for example, [36–41], and other references below). Moreover, we can also mention recent investigations conducted in other open spaces that were not intentionally designed as performance areas but where the sound field takes on special relevance, such as the Renaissance Palace of Charles V inside the Alhambra (Granada, Spain) [42] and several historical courtyards in Europe [43,44].

Recently, Astolfi et al. [37] discussed the applicability of ISO 3382-1 for performing acoustical measurements in ancient open-air theatres by using the theatre of Tyndaris (Sicily, Italy) as a case study. They reported excellent reproducibility in terms of the acoustic parameters when using two different measurement techniques (a dodecahedron source and firecrackers) included in ISO 3382-1. However, they expressed their concern regarding the regression analysis of the decay curves proposed in the standard for the estimation of the reverberation parameters. They argued that it is not appropriate for the analysis of the "cliff-decay curve linked to a few strong reflections" commonly registered in open-air sites. Previous studies had already drawn attention to this issue. Farnetani et al. [45] pointed out that the reverberation time (RT) behaviour in an open-air theatre differs from the classical reverberation theory. Moreover, Paini et al. [46] claimed that reverberation time (T_{30}) is not representative of "stepped decays" because, a priori, it does not give enough information about the real sound decay; it misses the initial step caused by the lack of early reflections and underestimates the late part result of the contribution of the isolated late reflections that could be easily heard. Meanwhile, in terms of subjective perception, van Dorp Schuitman and de Vries [47] demonstrated that the Early Decay Time (EDT) accounts poorly for the reverberance of rooms that have uneven absorption distribution. A few years later, Mo and Wang [48] also claimed that conventional reverberation parameters (RT and EDT) are questionable for judging the perceived reverberance in unroofed spaces that have uneven absorption distribution. They recommended that the spatial characteristics of the reflections arriving at each listener position be considered for describing the temporal attribute of reverberance. Despite the above-mentioned limitations, Chourmouziadou et al. [49] and Thomas et al. [50] found the reverberation time (T_{30}) to be an interesting parameter for comparing the sound field in different ancient theatres and urban squares (provided the potential inaccuracy of the obtained values is previously assessed in depth) since T_{30} is strongly dependent on the site geometry and only marginally depends on the listeners' locations.

Despite all the concerns regarding the applicability of ISO 3382-1 and the suitability of the acoustic parameters when dealing with open-air spaces, most authors continue to use ISO 3382-1 as a reference for measuring the acoustics of open-air sites. Despite its limitations, it is regarded as a guarantee of scientific rigour, repeatability and reliability when capturing the impulse responses and studying the acoustic behaviour of sites. Therefore, the methodology to be applied in this article was established by following, as far as practicable, the recommendations included in ISO 3382-1 [35], although we introduced some modifications due to the specific characteristics of rock art sites. In this respect, we followed the recommendations made a few years ago by Till [10]. This scholar stated that sound archaeology needs an alternative approach to the measurement protocol in order to account for the typical complex/irregular shapes of archaeological sites and to make detailed identification of potential acoustic effects possible. Till also claimed that the considerable uncertainties inherent to prehistoric sites force those testing the acoustics to take a flexible approach, both when defining the measurement protocol and in interpreting the results.

3.2. Acoustic Measurements in the Open-Air Core Rock Art Area of the Bacinete Complex

The experimental measurements in the core rock art area of the Bacinete complex were aimed at testing the hypothesis of the suitability of the Bacinete main shelter as a "natural auditorium" [20,21] (pp. 509–511), [29] (p. 152). As explained above, we also decided to test the adjacent site of Bacinete III [21] (pp. 499–500), [29] given the broad similarities between the two sites in terms of spatial arrangement: both sites have a flat, spacious area in front of the painted shelter in which a medium-sized crowd could have gathered and listened. The acoustic tests were undertaken on 10 and 16 June 2021. The purpose of the measurements was to gather a representative set of impulse responses (IR) from the selected sites to be used, in a first instance, to assess their acoustic properties in order to objectively relate the sound component of each site and its rock art. A second objective of the measurements, to gather data for auralisation purposes, will be discussed in a future publication.

An omnidirectional sound source (an IAG DD4 mini dodecahedral loudspeaker together with an IAG AP4GB power amplifier) was used to emit the excitation signal, a 12-s long exponential sine-sweep covering from 50 Hz to 20 kHz. Two positions of the sound source (S) were considered at each rock art site. These were selected according not only to the size and morphology of each of the sites but also to the location of the rock art. Six receiver points (R) were also distributed throughout the "zones of influence" of each source position. For the selection of the receiver locations, the non-diffuse condition of the sites was considered, trying to set enough test points to register the acoustics of the different "zones" created by the particular spatial configurations of the rocks. Inevitably, the number of S-R combinations included in the study was limited due to the time allowed for accessing the sites, which are on private land. Information about the S-R combinations analysed is provided in Figure 1, Tables 1 and 2. Furthermore, the spatial limitations caused by the height of the rocks, as well as the presence of vegetation and other particular elements, such as the protective iron fence installed around the main shelter, needed to be considered. It is also important to reiterate that there is no archaeological evidence regarding the use of the sites, meaning that details of the positioning of the sound source, the audience arrangement or the number of attendees in prehistory are not available. All these peculiarities meant that the equipment positioning had to be flexible, not only in the selection of the S-R locations but also in their height. For the height of the transducers, we worked with the hypothesis of a "standing audience". Only from that position were both the rock art panel and the sound source on the "stage" visible from all parts of the "audience area". Therefore, as far as practicable, the sound source was set at a height of 1.50 m and the receivers at a height of 1.40–1.50 m, which are assumed to be close enough to the average height of the ears of a standing speaker/listener [51,52]. Measurements were taken in unoccupied conditions.

At each selected receiver position, monaural IRs were registered with an omnidirectional microphone (micW n201) together with a high-quality audio device (Zoom F4), by using EASERA 1.2 software tool [53]. Spatial IRs were also gathered using a multichannel microphone (Zylia ZM) with its centre of coordinates always oriented towards the sound source. In this case, the excitation signal was played back using a Zoom H2n handy recorder and recorded with the audio software Plogue Bidule 0.9762. The captured spatial signals were post-processed in Matlab R2022a (The Matlab scripts used for the postprocessing of the IRs are available in the University of Barcelona repository at https://doi.org/10.34810/data649, accessed on 15 September 2022) in order to obtain the first and third-order ambisonic IRs, which were later analysed in several software tools (EASERA, ARTA [54], and IRSpatial [55]).

In the analysis phase, all the IR waveforms were carefully examined, focusing on their reflection pattern to better understand the effect on the acoustics of the site of any strong early reflections potentially coming from the rock formation. In this regard, the third order ambisonic IRs are used to estimate the direction of arrival (DOA) of the most relevant reflections, using the software tool IRSpatial [55]. The standard choices to assess the reverberation conditions of the space (T_{20} and EDT), sound clarity (D, C_{80}, T_s), and perceived loudness (G) were calculated. An in situ calibration method was used to calculate G [16,56]. In addition to these, the early lateral energy fraction (J_{LF}) was studied as a representation of the spatial behaviour of sound at those sites. The spectral behaviour of the selected acoustic parameters was analysed at each S-R combination individually, paying particular attention to the mid values in each of the zones of influence associated with each specific source position. This was performed in order to explore the spatial variability of the acoustics of the space. Spatially averaged values were then used to assess the behaviour of the space as a whole, providing an easy way to establish a comparison between the different rock art sites in the complex.

It is worth mentioning that environmental conditions, including temperature, wind velocity and background noise levels, were monitored during each measurement session. As far as possible, measurements were taken when wind speeds were negligible (less than 0.5 m/s), avoiding wind gusts. The temperature was approximately 34 °C and 31.5 °C, respectively, in the main shelter and Bacinete III. Air temperature variation at each shelter was less than 1.3 °C from the beginning to the end of the session, which is within the limits of the recommended maximum deviation of 2 °C [57]. Background noise at the complex was low enough not to cause any disturbance during the measurement sessions ($L_{Aeq} \approx 30$ dBA).

4. Results and Discussion

4.1. An Overview of the Impulse Response Structures and Reverberation Conditions in the Bacinete Core Rock Art Area

Considering that these shelters are open-air spaces where no diffuse sound field is expected, the analysis first focuses on the IR structures and reflection patterns. In general, the IRs captured at the Bacinete core rock art area show only a few early reflections after the arrival of the direct sound due to the rock formations, and almost negligible scattered sound energy caused by the landscape 100 ms after excitation. No late reflection that could cause an echo in any of the impulse responses registered is identified, and neither can any echo be discerned for speech or music according to the Dietsch and Kraak echo criterion [58]. Furthermore, as sound scattering depends on geometry, the irregular shape of the rock blocks avoids flutter echoes due to parallel walls, despite their proximity.

Even offering high impulse-to-noise ratio values (INR > 45 dB), this IR structure, frequent in open-air places, leads to a non-linear early decay curve (EDC), in which the influence of the direct sound creates an initial "cliff-type" decay in the integrated response [59], followed by about 100 ms of stepped decay produce by the infrequent strong early reflections (see some examples in Figure 5).

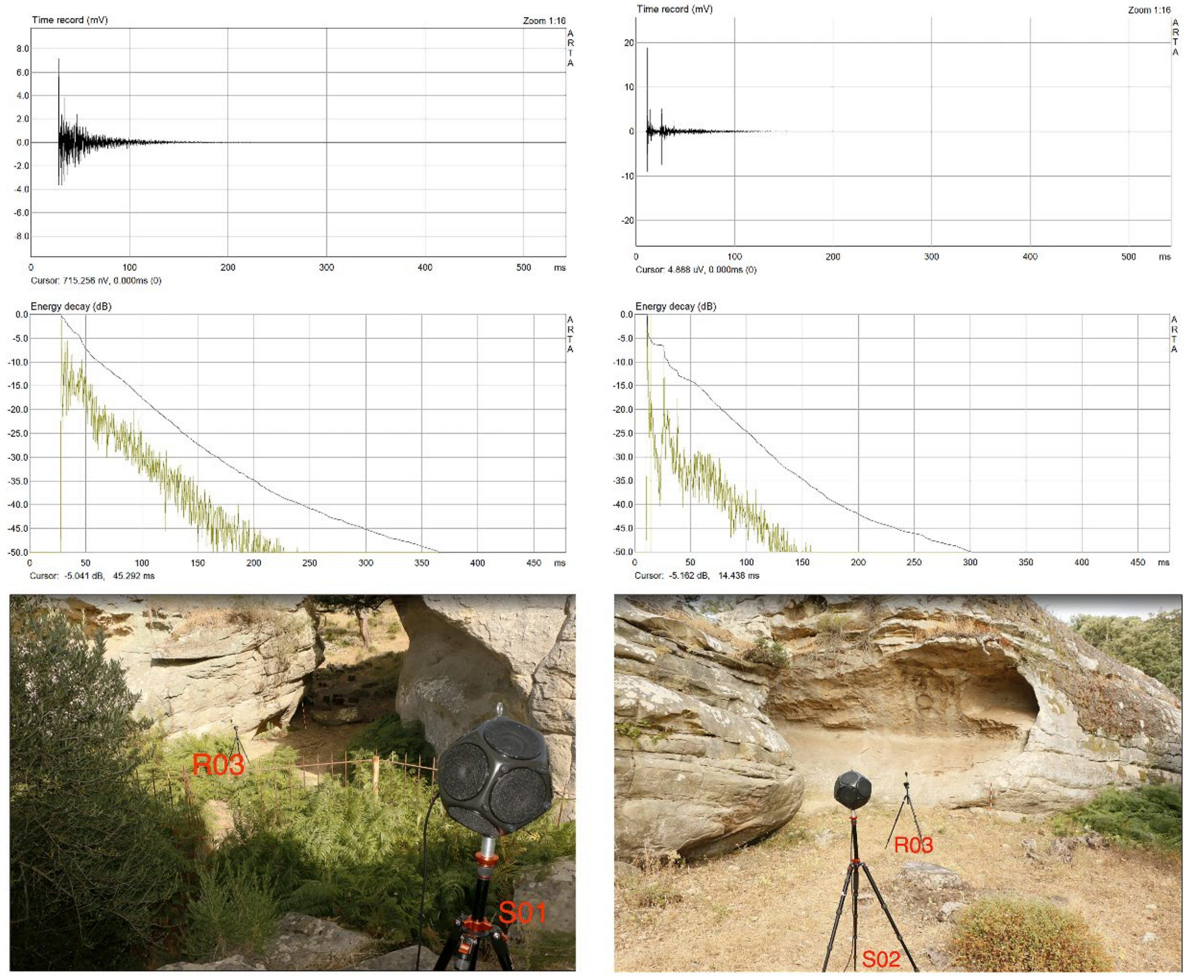


Figure 5. Impulse response (IR) and its early decay curve (EDC) captured at Bacinete main shelter with the source placed in front of the paintings (S1) and the receiver in the "audience" area (R3) (left column); and at Bacinete III, with the source in the middle of the audience area (S2) and the receiver next to the paintings (R3) (right column).

As previously mentioned, this type of EDC leads to an inaccurate estimate of the reverberation parameters. In view of this limitation, and following a recent study by Galindo et al. [60], the degree of non-linearity (ξ) has been studied so that it is considered when interpreting the results of the reverberation parameters obtained at the Bacinete rock art complex. The non-linearity parameter, ξ, as defined in Annex B of the ISO 3382–2 [61], quantifies the degree of EDC deviation (figures given per thousand) with respect to perfect linearity represented by a value of the square of the correlation coefficient (r^2) equal to 1. The standard establishes that ξ values greater than 10‰ indicate that the EDC is far from being a straight line and the value of the reverberation time estimated from this curve may be doubtful. Although in most of the IRs measured at the Bacinete main shelter and Bacinete III, the aforementioned linearity criteria are not strictly matched, meaning that this non-diffuse field affects the reverberation time calculations, ξ values are not extremely far from this criterion ($\xi \leq 10‰$), ranging between 7 and 17‰, except in a few S-R combinations (see Tables 1 and 2). Those S-R combinations that produce higher ξ values will be discussed in detail later. Therefore, although the reverberation parameter results should be interpreted with caution, the reverberation experienced at the sites is assessed through the analysis of the reverberation time, in order to present an initial insight into the Bacinete rock art complex acoustics and to establish a comparison between the different shelters.

Table 1. Mid values measured and averaged according to ISO 3382-1 [35] in the Bacinete main shelter.

ID Test	Reverberation Ratios			Energy Ratios			Loudness Param.	Spatial Param.	S-R Dist. [3]
	T_{20m} (s)	EDT_m (s)	ξ [1] (‰)	D_m (-)	C_{80m} (dB)	T_{Sm} (ms)	G_m [2] (dB)	J_{LFm} (-)	- (m)
BAm_S1_R5	0.37	0.32	16.928	0.89	15.40	21.95	−1.80	0.12	19.3
BAm_S1_R4	0.34	0.32	7.984	0.89	15.25	22.57	3.10	0.19	14.0
BAm_S1_R3	0.32	0.24	10.970	0.93	16.35	18.30	6.10	0.21	10.4
BAm_S1_R2	0.29	0.16	13.951	0.97	20.30	18.88	15.85	0.21	2.9
BAm_S1_R6	0.32	0.40	13.951	0.73	11.55	14.06	1.65	-	12.7
BAm_S2_R1	0.36	0.30	12.958	0.89	14.90	24.70	2.50	0.19	14.5
BAm_S2_R3	0.29	0.33	16.928	0.93	18.20	22.57	10.20	0.21	5.2
BAm_S2_R5	0.30	0.19	23.856	0.96	20.80	18.30	12.10	0.21	4.0
BAm_S2_R6	0.37	0.20	12.958	0.95	17.25	18.88	11.15	-	3.65

[1] Linearity factor calculated as defined in Annex B of the ISO 3382-2: 2008 [61]. [2] Reference signal information: in situ calibration method [16,56]. [3] Approximate values measured onsite.

Table 2. Mid values measured and averaged according to ISO 3382-1 [35] in the Bacinete main shelter.

ID Test	Reverberation Ratios			Energy Ratios			Loudness Param.	Spatial Param.	S-R Dist. [3]
	T_{20m} (s)	EDT_m (s)	ξ [1] (‰)	D_m (-)	C_{80m} (dB)	T_{Sm} (ms)	G_m [2] (dB)	J_{LFm} (-)	- (m)
BA3_S1_R1	0.27	0.11	13.951	0.98	23.5	10.4	9.95	0.13	10.0
BA3_S1_R2	0.24	0.31	12.958	0.91	18.8	20.3	8.85	0.13	7.7
BA3_S1_R3	0.28	0.14	6.988	0.97	21.8	11.5	13.70	0.23	4.8
BA3_S1_R4	0.27	0.30	21.879	0.92	19.7	16.0	12.00	0.16	3.9
BA3_S2_R2	0.31	0.20	15.936	0.95	20.1	10.9	9.55	0.13	4.1
BA3_S2_R3	0.30	0.28	11.964	0.95	18.6	14.6	7.85	0.23	5.3
BA3_S2_R4	0.30	0.29	11.964	0.92	16.7	16.7	5.55	0.16	7.2
BA3_S2_R5	0.29	0.12	13.951	0.97	21.2	12.4	9.50	0.34	10.0
BA3_S2_R6	0.34	0.19	37.639	0.95	20.2	10.3	5.05	0.19	6.5

[1] Linearity factor calculated as defined in Annex B of the ISO 3382-2: 2008 [61]. [2] Reference signal information: in situ calibration method [16,56]. [3] Approximate values measured onsite.

In closed spaces, reverberation time values above 1 s are common, and results in low-frequency bands are often significantly higher than at high frequencies, due to the absorption properties of their finishing materials and the air volume inside them. However, at Bacinete, we are dealing with an open space; thus, different results are expected. Figure 6 shows the spatially averaged values of the reverberation time (T_{20}) obtained in each shelter for each source location in each frequency band. As can be seen, the T_{20} values obtained in all the shelters are very low (well below half a second), with fairly flat behaviour throughout the studied frequency bands. These values, ranging from 0.25 to 0.35 s at mid frequencies (500 Hz and 1 kHz), are even below the common values found in small conference rooms (typically around 0.5 and 0.6 s in rooms with volumes of 50 to 1000 m^3 [62]). Despite this, they lie within the range expected for open conditions, being similar to those found at other open archaeological sites such as Stonehenge in its old configuration [63] (Table 3, Table 4 and Table 5) and other rock art shelters on the Iberian Peninsula [16]. A priori, this lack of reverberation, with T_{20m} of about 0.3 s, makes these spaces suitable for speech transmission [64]. Additionally, the observed spectral behaviour, with no significant enhancement either at low or high frequencies, suggests that the site cannot be considered to add any warmth or brightness to sound [65]. The reverberation time also shows very little dependency on the source–receiver combination (see error bars in Figure 6).

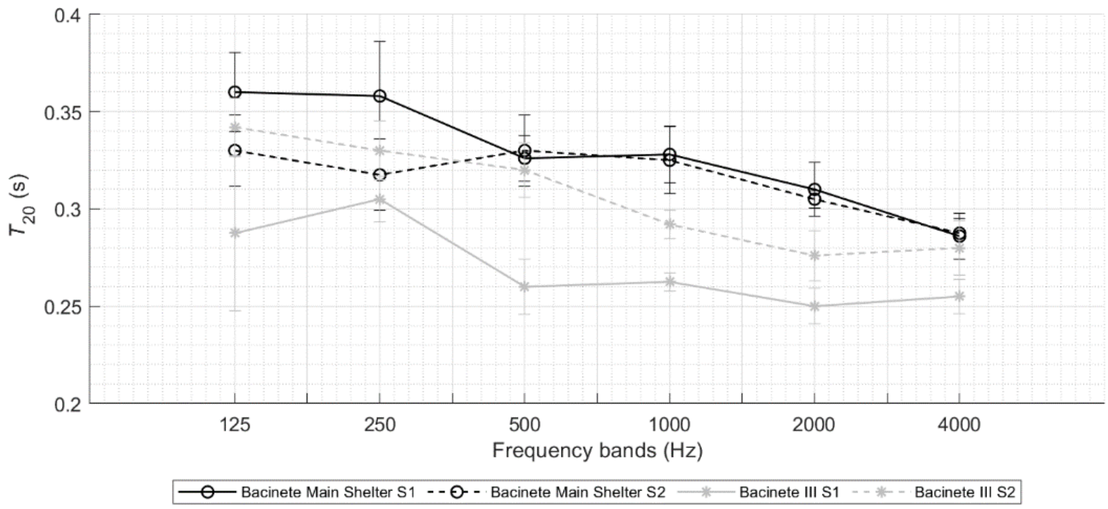


Figure 6. Reverberation time (T_{20}) obtained in each shelter of the Bacinete rock art complex: Bacinete main shelter; Bacinete III. Spatially averaged values for each source location are represented at each frequency band.

Returning to the visual inspection of the IRs, and focusing on their first part, the initial time-delay gap (ITDG) is analysed. The ITDG is defined as the time between the direct sound and the first significant reflection at a certain receiver position and had long been considered to be related to the acoustical intimacy [66] or, in other words, the listener's impression of the size of a room [65]. Furthermore, Mi et al. [67] determined through listening tests not only that the ITDG has a large impact on perceptual reverberation, but also that, for places with a reverberation of around 30 ms as in this case, small variations in ITDG (of about 18 ms) significantly influence the resultant perceived reverberation. Despite the low number of reflections present at Bacinete, determining which should be considered for the calculation of ITDG is not straightforward (see Figure 5 as an example), and for this reason, the exact ITDG values associated with each IR are not included here. Nevertheless, what is clear is that ITDG values are considerably shorter in all the S-R combinations (remaining well below 15 ms), presumably because the rock formations causing the first reflections are relatively close to the receiver positions. Beranek [68] reported that concert halls with IDTG values up to 20 ms were judged to have intimate acoustics, and the shorter the ITDG, the more intimate the experience. He also observed that lateral reflections are crucial for intimacy. It is worth mentioning that Lokki and Pätynen [69] recently discussed the concept of intimacy, claiming that it cannot be judged just through the ITDG, as sometimes considered [70], since this metric ignores other important factors, such as the perceived loudness or the direction of arrival of first reflections. In open spaces with a lack of a reverberant tail, Thomas et al. [50] also found a robust correlation between ITDG and other parameters measuring the fraction of early energy, such as C_{80}. All this suggests that the absence of reverberation and low ITDG values caused by the nearby rock formations may contribute to building a subjective feeling of intimacy in the shelters, despite the fact that they are open spaces.

At this point, and considering that these sites have a non-diffuse acoustic field, the variation in the results in the S-R positions studied is of particular interest for discussing proposed hypotheses for the site acoustics. Hence, individual results at each S-R combination are analysed from now on instead working with spatially averaged values, as recommended in the standard [35] and previous sound archaeology studies [10].

4.2. The Acoustics of the Bacinete Main Shelter

The analysis of the IRs gathered at the Bacinete main shelter was undertaken with the aim of carrying out a more rigorous study of the hypotheses raised by Díaz-Andreu and Lazarich [20,21] (pp. 509–511), and later mentioned by Solís [29] (p. 152), on the use of the main shelter as an auditorium. In their publications, Lazarich et al. and Solís present a thorough spatial study of the site, focusing on the spatial distribution of the rock outcrops. In the core area, both studies identify the space in front of the Bacinete main shelter as a natural theatre or auditorium, establishing in this way a non-explicit formal parallelism between the spatial distribution around the shelter and the traditional arrangement that has predominated in Western theatres and opera houses since the 17th century: the Italian style [71,72]. One of the main architectural characteristics of the so-called Italian style is that the stage or performance area is located in front of the spectators, on a higher level. This is the location of the rock art panels of the Bacinete main shelter in comparison to the area in front (the area identified as A in Figure 1). Lazarich et al. stated that "the concavity of the shelter acts as an acoustic shell amplifying and redirecting sounds from the "stage" area to the "spectators" area" [21] (p. 528). Just in front of the main shelter, the authors identified the audience area, a "lobby" or "stalls" area delimited by two rock outcrops (identified as B and C in Figure 1). The so-called stalls area is a relatively flat surface with a slight slope, and there are two "boxes" on the northern faces of these two rocky elements that could be considered the "upper gallery". Following this parallelism, it can even be considered that there is a space for the "pit" (or orchestra area) between the main shelter (stage) and the "audience", which today is covered by very tall ferns.

It must be clarified that, in this context, the theatre is understood as a space destined for holding scenic events, not necessarily recreational, but ritual, or any other social event that might involve sound. However, in contrast to what Solis appears to imply [29] (p. 151), Bacinete does not present the typical archaeological features of an aggregation site, an aspect discussed in detail in an article recently published by our team [16]. In this respect, although it was probably considered a special place for ritual activities, the absence of a significant number of archaeological finds with stylistic variability suggests that the site was not occupied consistently and repeatedly over a comprehensive period of time.

So that we could explore the initial hypothesis regarding the shelter being used as a theatre, the sound source was placed in front of the paintings, approximately in the centre of the "stage". In order to analyse the acoustics in each of the above-mentioned zones, four listener positions were distributed around the audience area: R3, R4 and R5 in the "stalls"; and R6 in one of the "boxes". Additionally, a receiver location was set on the "stage": R2 (Figure 1). The acoustic parameter results are summarised in Table 1.

As expected, when the sound source and the listener are both in the shelter (S1-R2), the listener perceives a reverberation level even lower than those listeners situated in the "audience" area (EDT_m = 0.16 s), which is due to the short distance between them (about 3 m). Furthermore, the significant influence of direct sound and the strong early reflections produced by the rock shelter itself cause extremely high values of sound clarity (D_m = 0.97 and C_{80m} = 20.3 dB). The rock shelter delimited the space at this site, similarly to the stage wall (*scaena frons*) in an ancient open-air theatre [39,73,74]. Thus, the sound reflecting on the shelter caused a significantly prompt first-order reflection towards the listeners in the "stalls", supporting the direct sound and, consequently, helping to improve the source loudness and sound clarity. The reflections caused by the shelter are of great intensity since it is a hard surface that barely absorbs sound. Nevertheless, the scattering effect of the shelter was limited due to the roughness of the rock formation. Thus, stating that the shelter acted like a shell able to focus the sound evenly on the audience was perhaps an overstatement. This is because the acoustic efficacy of a shell depends to a great extent on its shape and what is made of [75,76].

As the results show (see Table 1), Lazarich et al. [21] and Solis [29] were correct when they identified the "stalls" as a privileged area from an acoustic point of view. This, however, as the analysis of the impulse responses demonstrates, is not exclusively due to the reflections provided by the "acoustic shell" formed by the shelter, as they propose. To investigate the DOA of the main reflections, the spatial IRs captured with the Zylia microphone were analysed with the IRSpatial software tool. The direct sound from the source on the stage reaches the receivers in the stalls area without interference, since there are no physical obstacles that could distort sound propagation towards the receivers, and also due to the absence of a reverberant field. In the first 40 ms (approximately) after the arrival of the direct sound, there is a group of important reflections coming from the front, presumably from the rear panel of the main shelter. Immediately after this, there is a group of intense reflections coming from the rock outcrops designated B and C in Figure 1. These are more lateral and come from the upper plane, due to the shape of the rocks. Figure 7 shows an example of the analysis performed with the IRSpatial software tool.

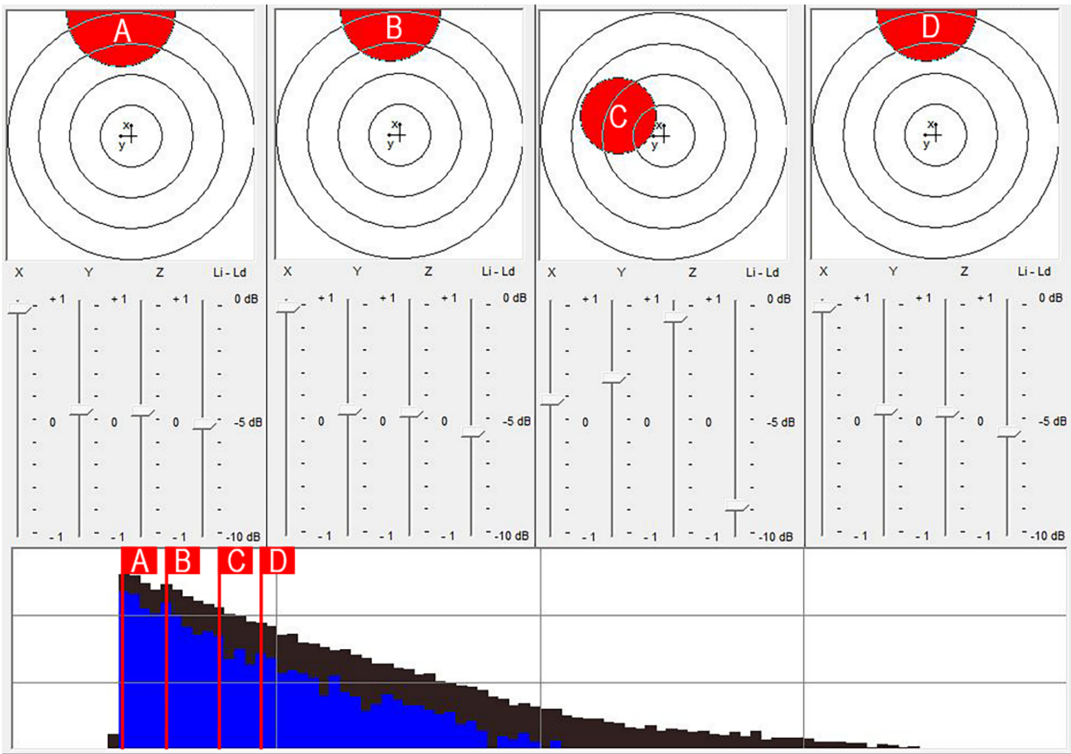


Figure 7. Example of the DOA analysis performed with the IRSpatial software tool. The 1st-order ambisonics impulse response corresponds to the S1-R4 combination in the Bacinete main shelter. Red dots show the DOA and the intensity of each group of reflections (A, B, C or D), the blue bars represent the sound intensity and the black bars the energy density of the signal.

Therefore, potential listeners in the "stalls" would have received significant early reflections from the lateral blocks, which would have reinforced the direct sound providing greater clarity and definition ($D_m > 0.89$, $C_{80m} > 15$ dB and $T_{Sm} < 25$ ms, see Table 1). These results indicate very favourable conditions for speech transmission. Music would also have been heard very clearly in the "stalls". However, as commonly found in other open-air sites, e.g., Roman and Greek theatres, C_{80m} values are possibly too high, exceeding the upper range limit criteria set for roofed concert halls and auditoria taking into account different types of music [77,78]. Additionally, as a considerable number of these early reflections arrive late rally at the reception points R3 and R4, values of $J_{LFm} \approx 0.20$ are obtained. These values are higher than expected at an open-air site, considering that the J_{LF} is related to the spatial impression [79] and such averaged values are similar to those measured in popular concert halls [78,80]. Centre time is considered not only as a cue of clarity of sound as usual;

rather, it is seen as an indicator of the presence of late reflections and echoes due to its sensitivity to late energy. This is because no prior division of the impulse response between early and late sound is considered [46]. In view of the low T_{Sm} values obtained (between 13 and 37 ms), it seems there are no reflections that are able to shift the impulse response centre of gravity to higher values.

Lazarich et al. also referred to a natural amplification in terms of the level subjectively experienced in this area when sound is emitted from the "stage" [21] (p. 510). This subjective feeling is corroborated by the G_m values obtained in R3, R4 and R5, which are 3 to 6 dB higher than the expected level in the free field using the same system configuration (see Figure 8). The just noticeable difference (JND) for G is set as 1 dB [10], and therefore it can be said that there is a significant natural amplification of sound caused by the shelter at those positions. Actually, as has been pointed out in the literature, spatial perception has been proven to increase not only with the density of early lateral reflections but also with the early sound level [81]. Therefore, these high G values would have reinforced the spatial impression created by the lateral early reflections denoted by considerable J_{LFm} values. In combination with the absence of reverberation and the low ITDG values obtained, these greater J_{LFm} values are possibly responsible for the subjective feeling of intimacy reported by the authors.

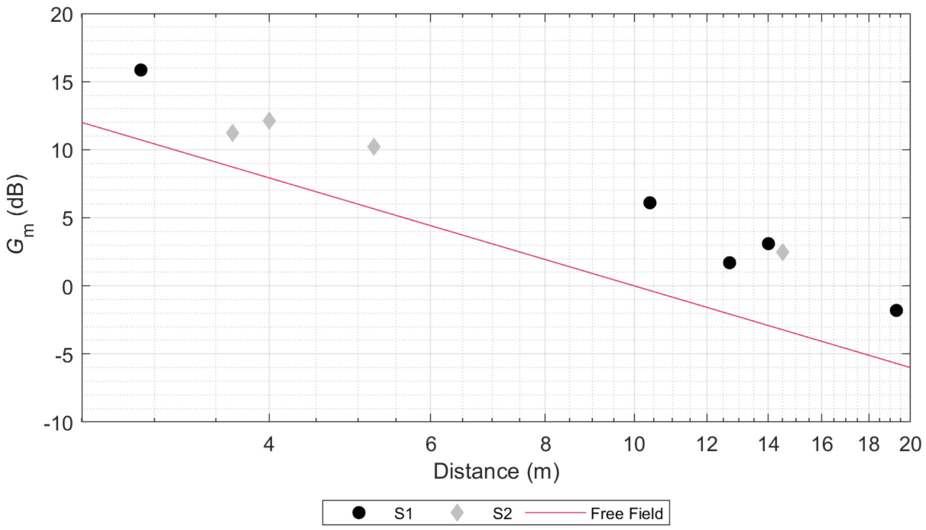


Figure 8. Sound strength, G_m (dB), spectrally averaged values calculated from the measured IR in the Bacinete main shelter. The theoretical free field propagation is represented by the red line.

Lazarich et al. [21] (p. 510) also mention that the "boxes" of the "upper gallery" could be considered privileged positions in terms of visibility and listening conditions. Looking at the results obtained for S1-R6, however, nothing objectively supports the idea that listeners in those positions would have experienced better acoustics than those in the "stalls" due to the acoustic features of the site. Even the sound clarity parameter values (D_m and C_{80m}) are slightly reduced. Nevertheless, an improvement in the visual cues in those upper positions might have led to a subjective feeling of improvement in acoustic perception [82].

Trying to put aside the presumption that the space was used as a theatre since it can be considered an idea influenced by the human ability to establish a parallel between the natural arrangement of the rocky blocks and the architectural elements of a theatre, one further hypothesis on the use of the site was explored. In this case, the sound source was located in the middle of the area previously designated as the "stalls" (S2 in Figure 1), considering the "stage" part of the area for the listeners. The results in Table 1 show that the acoustic experience of the potential listeners is very similar in comparison to the previous hypothesis in terms of reverberation and clarity of sound. The main difference is that the S-R distance is now much shorter, except in the "stage" area, so the sound level registered at the receiver locations is higher. Furthermore, the reflection pattern changes considerably.

Through the analysis of the spatial IRs, it can be seen that, with the source located in S2, frontal and lateral reflections are produced by the upper part of the rock formations B and C, and the role of the painted shelter is almost negligible since it only produces sporadic reflections of very low intensity. In any case, the areas where the listeners would have been located continue to receive a considerable number of early lateral reflections, as indicated by the J_{LFm} values (Table 1). Therefore, although this configuration reduces the number of attendees with visibility of the sound source, it could also have been favourable for speech transmission since the listeners received the message with a higher sound level than when the source is located on the stage.

4.3. The Acoustics of Bacinete III

A similar analysis to the one described in Section 4.2 was performed at Bacinete III. The measurement campaign was designed to answer two main questions: Could the area in front of Bacinete III have also been used as a place for a medium-sized group of people (slightly larger in numbers than at the main shelter) performing rituals and/or social events? Were the acoustic conditions of this site suitable or advantageous for such a use in comparison to those found at the Bacinete main shelter? Two sound source positions and six receiver locations were set for the acoustic measurements: S1 was placed next to the paintings on the rock formation, in a position raised about 2.70 m from the floor, and S2 was placed approximately in the middle of the rock formations. Following the same inspiration in Italian-style theatres as in the Bacinete main shelter, S1 would have been on the “stage” and S2 in the middle of the audience area. The receiver designated R5 was also on the stage, and the receivers from R1 to R4 were distributed throughout the audience area, withR6 being located in the farthest position from the paintings, right in front of a small boulder.

The results obtained for the different acoustic parameters are summarised in Table 2. As expected, the acoustics experience at the site is again defined by the lack of reverberation (T_{20m} of about 0.30 s) and the presence of strong early reflections that produce considerable clarity of sound (D_m > 0.91, C_{80m} > 16 dB and T_{Sm} < 20 ms). However, as denoted by the J_{LFm} values, at Bacinete III fewer early lateral reflections than at the Bacinete main shelter reach the listener positions (except those set next to the rock formations) since the distance between the rock formations at the sides is greater in this case. Hence, lower J_{LF} values, meaning lesser feelings of a spatial impression than at the Bacinete main shelter, would have been experienced. Furthermore, the shape of the rocks leaves, in this case, the audience area completely uncovered, which leads to a prevalence of reflections on the horizontal plane. This means that at Bacinete III, reflections from above those of the Bacinete main shelter that might have supported such subjective feelings of “being inside a place” were not received either. Consequently, even though at Bacinete III there is more space for congregation, and reverberance and clarity conditions are comparable to those experienced at the Bacinete main shelter, the audience area is more open than that considered in the other shelter. As a result, listeners would have perceived a lesser feeling of spatial impression in Bacinete III than in the Bacinete main shelter. In terms of loudness, in both configurations considered at Bacinete III, a high enough sound level would have reached the listeners. Only when the source or the receiver was placed in the rock shelter next to the paintings (meaning the source was placed at S1 at all the receiver points; and at R5 when the source was placed at S2) did the intense early reflections produced by the shelter result in a perceptible natural amplification of sound (G_m values well above the free field curve, see Table 2 and Figure 9).

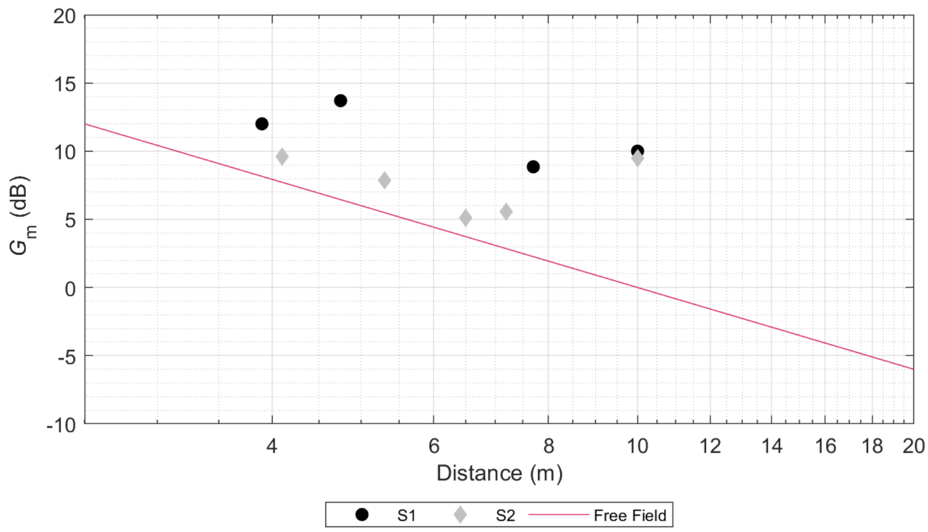


Figure 9. Sound strength, G_{m} (dB), spectrally averaged values calculated from the measured IR at Bacinete III. The theoretical free field propagation is represented by the red line.

Furthermore, examining the DOA of the main reflections in IRSpatial in the same way as at the Bacinete main shelter, it is possible to observe that when the source is located next to the paintings (S1 position), most of the sound energy that reaches the potential listeners comes from the front, except for some lateral reflections. Conversely, when the source is located in S2, potential listeners receive the direct sound from the front, followed by about 30 ms dominated by strong lateral reflections produced by the lateral blocks. After these reflections, a group of lower-intensity reflections coming from the rear (i.e., the painted shelter) is discerned. When the reflections coming from the rear are intense and delayed enough in comparison to the direct sound, they affect intelligibility in the receiver positions closest to the painted shelter. As a final comment, it is worth mentioning that this lack of lateral reflections could be the reason why the averaged reverberation time estimated with S1 in Bacinete III is even lower than that found in the other configurations studied, both in Bacinete III and in the Bacinete main shelter (see Figure 6).

5. Conclusions

This article has presented the results of a thorough acoustic measurement campaign carried out in the rock art complex of Bacinete, Cádiz province (Spain). The discussion has focused on what we have designated as the core rock art area in the complex, which contains five painted shelters. The so-called main shelter stands out over all the others for several reasons, the first being the presence of two different artistic styles, with the oldest —the Laguna de la Janda style—being unique in the whole complex. The site also contrasts with all the others because it has the largest number of motifs and they were painted in at least five distinct phases. The Bacinete main shelter is also remarkable because it is more elevated than the area in front of it, loosely reminding us of the layout of an Italian-style theatre, which has led rock art researchers to propose that it acted as an auditorium [21,83]. An initial analysis of its acoustics appeared to indicate that there was a certain amount of reverberation that may have helped create the right atmosphere for any events that may have taken place there [20]. However, the simplicity of the method used at that time called for a revision of the tests to identify the acoustic properties of the site making use of more sophisticated field methods. In addition to the main shelter, the study was expanded to include the nearby site of Bacinete III, also located in the core rock art area of the complex. The latter is more modest in terms of the number of motifs, style (only Schematic) and has no distinct phases. Nevertheless, both sites have in common panels located in shelters with a raised base and an area in front that could have been used by a potential audience.

In the acoustic measurement campaign, a representative set of monaural and spatial IRs was gathered onsite and analysed according to the ISO 3382-1 standard, adapting the methodology to the special requirements of open-air rock art sites. The use of a high-order ambisonic microphone allowed for the acoustic analysis of the 3D sound maps obtained for each source–receiver combination in the software tool IRspatial. Such maps helped us investigate the role of the painted shelter in the acoustics of each site by identifying the direction of arrival of the main early reflections present in the measured IRs. The results obtained suggest that the Bacinete main shelter offered favourable conditions for speech transmission, and that music would also have been heard very clearly when the sound source is located either next to the paintings or in the middle of the listeners' area. Moreover, when the sound is emitted next to the paintings, the perceived loudness reinforces the spatial impression created by the significant lateral early reflections produced by the rock formations at the sides. Considering the absence of reverberation and the low ITDG values obtained, these reflections are possibly responsible for the subjective feeling of intimacy experienced onsite, as previously reported by Lazarich et al. [21]. Similar acoustic conditions in terms of reverberation, sound clarity and perceived loudness were found at Bacinete III when the source was located next to the paintings. Given these results, we would argue that the reason archaeologists have never considered this area as a possible "auditorium" is related to the differential aural impression obtained in each of them. In the main shelter, the combination of acoustic features and the unique visual impact of being surrounded by those large rock formations could also have exclusively enhanced this site with a subjective feeling of intimacy in front of the shelter, the area with the potential for being used as an "audience area" [69,84]. In contrast, at Bacinete III the spatial impression or subjective sensation of spaciousness would have been less significant, as the space was more open. It must be borne in mind that the lack of archaeological evidence regarding the uses of the sites, makes it difficult to accurately assess the acoustics environment experienced by prehistoric people in real conditions, since details such as the position and nature of the sound source and the number and positioning of attendees, may have implied changes in sound propagation.

Was the Bacinete main shelter ever used for social or ritual activities? Intangible practices leave no apparent evidence, although archaeology has developed ways to deduce them. We would like to argue that a careful excavation of the areas in front of the shelters, including a series of micromorphological analyses, may assist in identifying with a higher degree of certainty the use of the space in that area. For now, we can only say that the universal social understanding of the senses [85], and in particular of hearing [86], makes it highly likely that the past communities who created and used the Bacinete rock art complex were sensitive to its acoustic properties. This means that, if it were somehow special, it is likely that its sonic component played an important part in how people interacted with it.

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