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A new protocol for the reconstruction of the auditory ambiance in Palaeolithic sites: first results from Grotta Paglicci (Apulia – Southern Italy)

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Abstract **– We present the first results of the archaeoacoustic investigations at Grotta Paglicci (Apulia - Southern Italy), a Palaeolithic site remarkable for the finding of some portable art objects and for the presence of wall paintings. Significant differences in the acoustic properties among the three main internal rooms, which might have been relevant for Paleolithic hunter-gatherer's use of the cave were recorded. Building on this interesting data, we propose a new protocol that combines the collection of the acoustic measures *in situ* and their application to an editable 3D cave model.**

This interdisciplinary approach will allow the analysis of reliable acoustic data sets on which the application of computational techniques could open new scenarios in the exploring of intangible aspects of human behavior in the Palaeolithic.

1 INTRODUCTION

The archaeoacoustics of Palaeolithic sites is a multidisciplinary field of research aimed at understanding the acoustic and auditory aspects of past human behavior. In this regard, the analysis of perception in rock art caves/shelters can provide new ways to correlate the tangible and intangible aspects of the past communities that occupied these sites [1]. The main steps of this research include:

1_ the investigation of the 3D spatial properties of sound to gain a better understanding of the acoustic environment experienced by past rock art producers.

2_the prediction of the acoustic conditions of rock art sites using virtual auralization to recreate the behavior of different types of sounds.

Concerning the archaeoacoustic investigations inside Palaeolithic caves, the application of acoustic measurements collected *in situ* on an editable 3D model appears to be essential. This is due to the need to reconstruct, through the analysis of archaeological sedimentological and geological records, the space layout investigated during the period when human activities occurred. In this work, acoustic measurements employing the SineSweep technique inside the three internal Rooms of Grotta Paglicci (Apulia – Southern Italy) were conducted. In addition to presenting the first data from these applications, in this paper we propose a new protocol that combines the collection of the *in situ* acoustic measurements and their application on a 3D cave model created through innovative techniques. This procedure will allow us to achieve more reliable data related to the acoustic dynamics and potential uses of the caves by prehistoric hunter-gatherers.

2 MATERIAL AND METHODS

A. The site of Grotta Paglicci

Grotta Paglicci opens on the western slope of the Gargano promontory (Apulia, Southern Italy). The site comprises the present-day cave and a collapsed more external hall that was part of a wider hypogeum complex during the Palaeolithic (Fig. 1). In addition to a rich and thick stratigraphical sequence spanning from Aurignacian to late Epigravettian (between 40,000-13,000 years ago) brought to the light in the *atrium* of the cave, the site is remarkable for the only Palaeolithic wall painting discovered in Italy so far [2]. It's represented by two horses and a series of "positive" and "negative" depictions of hands realized, probably during the Gravettian (~30,000-25,000 years ago) in the Room 3 (Fig. 2). Beside this, part of a parietal picture (a limestone block representing a hind quarter of a horse), possibly located on the vault which later collapsed, was found in the *atrium* at the base of an early Epigravettian layer. Moreover, a series of graffiti, dated to a period not later than 15,000 years ago, is present on the wall of the present-day entrance of the cave. Finally, several Gravettian and Epigravettian portable art objects were recovered from the excavation of the deposit in the *atrium* [3].

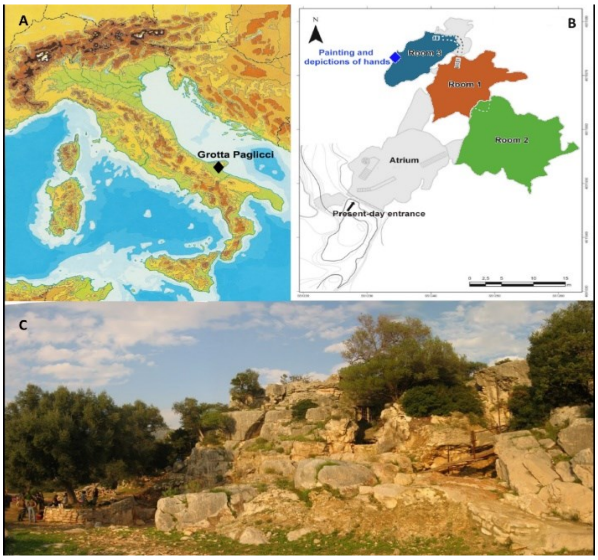

Fig. 1: A_Location of the site; B_Planimetry of the cave; C_External view of the site

B. The acoustic tests in situ

The collection of the acoustic measures *in situ* involved the use of a dodecahedral sound source to emit the test signal and a dual microphone system, a class 1 omnidirectional microphone and a 19-capsule spherical microphone array, to acquire the acoustic response of the various environments to be characterized. The spherical microphone array is represented by a 19-capsule array Ambisonic microphone array with high-end 24-bit recording resolution, distributed by ©Zylia company (www.zylia.co). This device does not require calibration before taking measurements. An Exponential Sine Sweep (ESS) was used as the test signal, selecting an appropriate length for the environment and with frequency range 20-20,000 Hz. The main advantages of this measurement technique, developed by Prof. Farina of the University of Parma [4], are:

1. High signal-to-noise ratio allows for accurate measurements even in environments with background noise
2. Ability to separate linear response from non-linear distortions enables isolation of the pure acoustic response of the environment
3. Immunity to temporal variations reduces the influence of acoustic disturbances during measurement
4. Energy efficiency: distributes energy optimally across the frequency spectrum

The test signal was played simultaneously by all twelve speakers of the dodecahedral sound source (Look Line "Model Kit103“) [5] and acquired by both the Zylia ZM-1 spherical microphone array. Processing the acquired signal by deconvolution with the inverse signal allowed the determination of the impulse response of the environment. By operating on the impulse response obtained from the omnidirectional microphone, it was possible to estimate all the monoaural acoustic parameters of the environment under test. Using the spherical array of microphones and the Ambisonics technique, it was

Fig. 2: Room 3 with wall paintings

possible to decompose the incoming sound into spherical harmonics, and to analyze the direction of arrival (DOA) of the sound, highlighting possible sound phenomena such as reflections on the walls. In addition, the use of a panoramic image captured by a 360-degree camera as a background, allows the creation of a dynamic map of the "Spatial Power Density Level" [dB/sr] of the cave's impulse response. The software was developed by the start-up company TTRED Srl [6].

The measuring focused on three key acoustic descriptors, each providing specific information about the sound behavior in the three Rooms of Grotta Paglicci:

1. Reverberation Time (T20): measures the time required for the sound pressure level to decay by 20 dB (extrapolated to a 60 dB decay). It is expressed in seconds and indicates how long sounds persist in a space after the source stops. Longer reverberation times create a sense of spaciousness but can reduce speech intelligibility, while shorter times provide clarity but may lack warmth and fullness.
2. Clarity C50: this parameter, measured in decibels (dB), quantifies the ratio of early sound energy (arriving within the first 50 milliseconds) to late sound energy (arriving after 50 milliseconds). It is specifically designed to evaluate speech intelligibility—higher C50 values indicate better speech clarity, while lower values suggest poorer intelligibility.
3. Clarity C80: similar to C50 but with an 80-millisec-ond threshold, C80 is optimized for assessing musical clarity. It measures the ratio of early sound energy (first 80 milliseconds) to late energy. Higher C80 values indicate better definition and articulation of musical notes, while lower values suggest a more blended reverberant sound character.

These parameters, analyzed across different frequency bands (typically octave bands from 125 Hz to 16,000 Hz), provide a comprehensive characterization of the acoustic properties of each Room.

C. The 3D model of the cave

The 3D cave model (Fig. 3) was created using SLAM-based LiDAR technology that combines two methods: LiDAR (Light Detection and Ranging) and SLAM (Simultaneous Localization and Mapping). LiDAR sensors measure a detailed 3D point cloud of the surrounding space, while SLAM algorithms process this data in real time, tracking the movement of the LiDAR

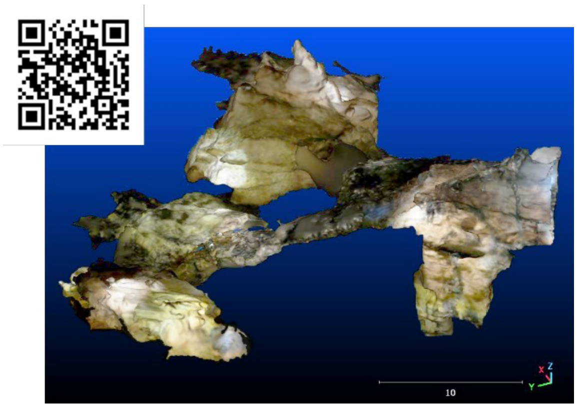

Fig. 3: The QR code and an image of the 3D model

sensor within that space. The 3D point cloud produced was then processed to build the textured model of the cave in mesh format. The latter was decimated (to approximately 330,000 faces) to use simplified geometries, reducing calculation times, while maintaining the fundamental geometries of the study area [7].

3 RESULTS

The characterization of the acoustic properties of the three internal Rooms of Grotta Paglicci, revealing significant differences that might have been relevant for prehistoric populations (Fig. 4, 5 and 6).

Room 3 (blue color)

Reverberation Time (T20): shows intermediate values (0.5-0.55 seconds) with a relatively uniform distribution across frequencies and a gradual decrease toward high frequencies. This suggests an acoustically balanced environment.

Clarity C50: displays non-uniform behavior with high values at low frequencies (8 dB at 125 Hz), an evident minimum in mid-frequencies (2 dB at 1000 Hz), and an increase at high frequencies. This characteristic might create a particular perception of the human voice, with good intelligibility for low and high sounds, but relative confusion in the middle frequencies.

Clarity C80: follows a similar trend to C50, confirming the acoustic peculiarity of this room for musical listening, with a possible "shadow zone" in the central frequencies.

Room 1 (orange color)

Reverberation Time (T20): shows the lowest (0.3-0.4 seconds) and most constant values among the three rooms, indicating an acoustic "dry" environment with minimal reverberation.

Clarity C50: presents the highest values (7-13 dB) across almost the entire spectrum, ensuring excellent speech intelligibility. The curve shows a generally increasing trend toward high frequencies.

Clarity C80: confirms the excellent acoustic clarity of this room with high values (12-20 dB) throughout the spectrum, ideal for perceiving musical details.

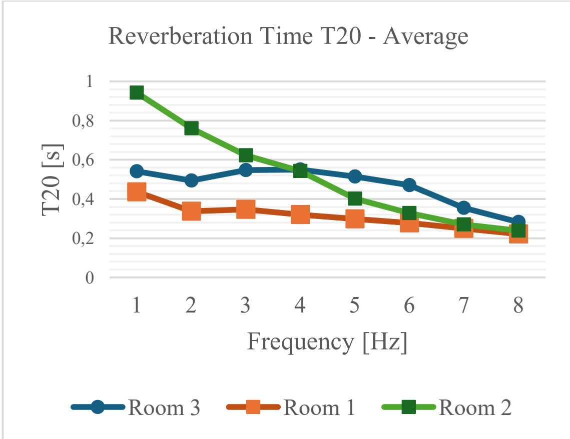

Fig. 4: *Reverberation Time T20 as a function of frequency (octave bands) recorded in the three internal Rooms of Grotta Paglicci*

Room 2 (green color)

Reverberation Time (T20): shows the highest values at low frequencies (over 0.9 seconds at 125 Hz) with a marked decrease toward high frequencies (0.3 seconds at 4000 Hz and above). This behavior is typical of environments that favor the resonance of low sounds.

Clarity C50: shows very low values at low frequencies (2 dB at 125 Hz) but a strong increase at high frequencies, suggesting poor intelligibility for male voices (deeper) but better for female voices or high-pitched sounds.

Clarity C80: Follows a trend similar to C50, with a very pronounced positive slope as frequency increases.

4 CONCLUSIONS

Several research carried out in Palaeolithic painted caves shows a relationship between paintings or signs, and the sounds that might have been produced adjacent to them [8-15]. However, these investigations were conducted using the equipment available at the time, which is now obsolete compared to the new measuring instruments available today. Furthermore, the acoustic response detected refers to the actual internal conformation of the caves investigated, which may have been different from that present during the Palaeolithic.

In this work an interdisciplinary approach focused on emerging technologies able to facilitate and to improve the analysis of specific acoustic features in Palaeolithic caves were performed.

The precision of the ESS technique allowed for detailed characterization of the acoustic properties of the three internal Rooms of Grotta Paglicci, revealing significant differences that might have been relevant for Palaeolithic hunter-gatherers. The acoustic measurements collected *in situ* will be applied to a 3D model of Grotta Paglicci created using the SLAM-based LiDAR technology. Through the editable 3D model, the probable layout of the investigated spaces during the period when human activities occurred can be reconstructed. The application on this “virtual environment” of an acoustic CAD will permit a more reliable reconstruction of the auditory ambiance of Grotta Paglicci during the Palaeolithic period.

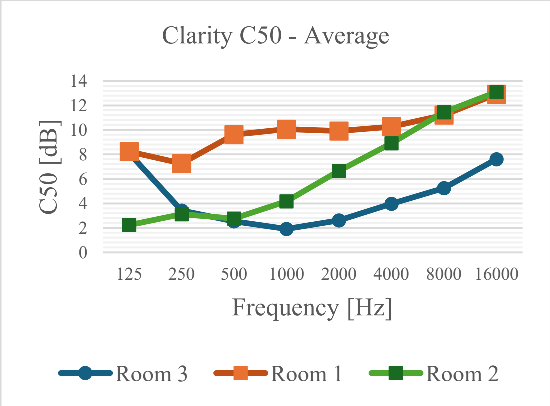

Fig. 5: Clarity C50 as a function of frequency (octave bands) recorded in the three internal Rooms of Grotta Paglicci

The detailed measures captured *in situ* will facilitate comprehensive analysis and interpretation. Besides the obtaining of reliable data, the adoption of this method could be useful to reduce access to these peculiar areas, ensuring a better preservation of the archaeological records.

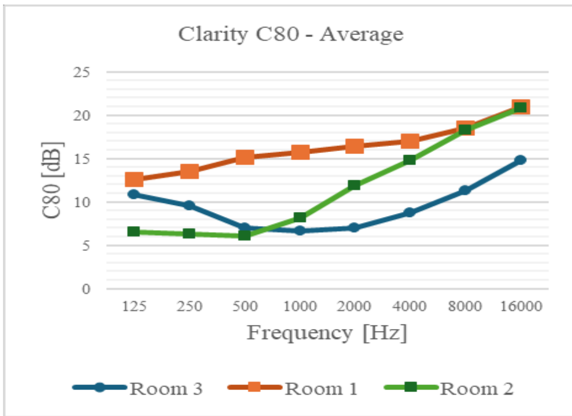

Fig. 6: Clarity C80 as a function of frequency (octave bands) recorded in the three internal Rooms of Grotta Paglicci

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