Speleoacoustics in Southern Ardèche for Auralizations and Music Experimentation

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ABSTRACT

Caves are archetypically considered to be large-volume and therefore lengthy-reverberating, resonant spaces, and have not been given much consideration in terms of the enormous variety of acoustical environments that they contain. Though cave acoustics have been studied, beyond a recent model of Lascaux we have not seen computational models of cave acoustics as a research focus; for the purpose of relating cave acoustics to human uses of caves, we are engaged in new collaborations to create data-driven acoustical models and auralizations. Here, we propose a human-centered acoustical data collection strategy to enable physics-based and psychoacoustically accurate spatial reconstructions of cave acoustics. These reconstructive models can be used to produce audio demonstrations of cave acoustics in which different sound sources can be auralized. We summarize 2021 speleoacoustics measurements that we made within limestone caves in the Ardèche Valley of south-central France. These measurements reflect methodological propositions for fieldwork relating spatial acoustics to human sensory experience and associated anthropological concerns. We also compare a range of different acoustical features corresponding to specific and contrasting geomorphological contexts in related cave systems. Further, our study was conducted to prepare for future archaeoacoustics research that will offer virtual access to cultural heritage acoustics. These data can be used to produce experiential simulations that create new spaces for musical experimentation.

1. INTRODUCTION

We propose here the term "speleoacoustics" to refer to acoustical studies of caves most generally, whereas "archaeoacoustics" is the name of the field concerned with the study of acoustics in relation with archaeology [1], that is, the study of human life from its materials remains, and therefore a specific interdisciplinary science [2]. Following previous work on Ardèche cave acoustics [3], in conversation with Monteil for expertise on karstic and archaeological background of Ardèche Caves [4, 5] and with Kolar about archaeoacoustical premises, Valentin selected the two caves for the present study according to the following research propositions.

We designed the research discussed here for the purposes of 1) testing the feasibility and in-cave performance of specific audio and documentation equipment for speleoacoustics research; 2) cross-comparing the performance of equipment and measurement signals across a range of cave settings in preparation for a larger research collaboration on the acoustics of caves decorated during the Upper Paleolithic; and 3) collecting and analyzing "human-centered" speleoacoustical data for the purpose of reconstructing cave acoustics in auralizations.

2. DATA COLLECTION METHODOLOGY

2.1 Caves Selected for Fieldwork

Saint-Marcel Cave (La Grotte de Saint-Marcel) and l'Ours Cave (La Grotte de l'Ours – "the cave of bears") are located in the Ardèche Valley of south-central France (in the Municipalities of Vallon-Pont-d'Arc and Bidon, which are 13km apart) which is known in geomorphological terms as a karstic massif of cretaceous limestone drilled during the late Miocene by the Messinian Salinity Crisis [6]. Saint-Marcel Cave covers more than 64km with a vertical drop of 325m and a natural entrance altitude of 95m. l'Ours Cave covers approximately 90m but exists as part of a larger cave system uniting several caves along the valley of the Ibie River (a tributary of the Ardèche River), with an entrance altitude of 200m. The two caves are comparable in terms of their karstic and geological features, but with different geomorphological profiles.

In speleological terms, distinct paths for the passage of ancient rivers are called "galleries". The galleries of Saint-Marcel Cave are very wide (10m to 30m by up to 40m high) with various calcite formations (active or non-active, depending on the location) in some areas. l'Ours Cave is narrower with a main gallery that is approximately 5m wide and 10m high, with non-active calcite formations. Both caves present historical and archaeological use-evidence, with cultural materials previously identified around their historical entrances.

We selected both caves on the basis of their physical and cultural profiles, and also to study features similar to those in the nearby Grotte Chauvet, a venue in which we began fieldwork in March 2022. The relative accessibility of the selected caves was important to our purpose of initiating joint fieldwork between archaeoacoustician Kolar and spelunker Valentin, with the support of local caves expert Philippe Monteil. Saint-Marcel and l'Ours are both referenced as "Grade 1 caves" (they do not require the use of any spelunking equipment other than a helmet with lighting) by the French Federation of Spelunking. Both caves in which we conducted this fieldwork have evidence of past human uses; however, our purpose here was not the integration of our speleoacoustical research with archaeological data, but rather, the documentation of particular cave features in terms of a human-centered data collection method. This work produces spatially accurate documentation of human perspectives on a specific soundfield context, enabling realistic auralizations over headphones [7].

2.2 Equipment for Speleoacoustical Measurements

One goal of this fieldwork was in-cave testing of the performance of audio equipment and source test signals. Speleoacoustics research is logistically constrained by the location and conditions of caves. First, and as with spelunking, the portability and durability of the gear necessary for cave activities is one of the main points to consider. Even if the accessibility of the caves is ensured, transporting the gear to rural cave entrances and throughout cave environments presents challenges in terms of form-factor, weight, and number of bags. Second, gear must be self-powered, which reduces the selection of equipment for both sound sources (loudspeakers and impulse-generation tools) and receivers (microphones, preamplifiers, and audio recorders, as well as recording devices, including audio interfaces and computers). Third, climate conditions had to be monitored to observe equipment reliability in cave conditions, as well as produce documentation to track the speed-of-sound for certain analytical techniques. Thanks to the Amprobe C02 meter, we were able to track temperature, humidity and the C02 levels that can affect human health and safety in limestone caves, as listed in Table 1.

We used three setups for impulse response (IR) measurements, the standard technique for documenting the acoustics of enclosed spaces. 1) For synchronous playback and recording of audio signal sources, our most complicated setup employed a Meyer MM-4XP precision loudspeaker and a JBL BassPro SL 8" compact subwoofer, both powered by the Jackery Explorer 240W Portable Power Station though used sequentially in playing test signals. The measuring laptop computer used as its USB-audio interface a Zoom F8N field recorder, running Digital Peformer 10 software both to play the audio signal of a 40-second all-pass chirp that we had generated in Matlab from code by Jonathan Abel, and also to record the "room" responses ("synchronous playback and recording"). Post-processing was then necessary to convert these raw response recordings into impulse responses, again using a Matlab script by Abel. 2) For asynchronous measurements (where playback and recording equipment is not interconnected), we played the same 40-second all-pass chirp from an iPhone plugged into a portable omnidirectional loudspeaker, the Bose Soundlink Revolve Plus II. The raw responses from these asynchronous measurements were likewise processed into IRs using a customized Matlab script by Abel. 3) For the most portable impulse generation system, we carried with us two pairs of wooden clappers. For receivers, we used through Zoom recorder preamplifiers one pair of AuSIM in-ear omnidirectional microphones (Sennheiser KE4-211-4 capsultes) and two Behringer ECM-8000 omnidirectional measurement microphones. Additionally, we used two first-order Ambisonics (FOA) microphone arrays (set to record in 4-channel A-format) via Zoom H3VR field recorders that we configured in the custom setup discussed below.

Amprobe	Temperature [°C]	Humidity [%]	C02 [ppm]
Saint-Marcel	12.1 to 14	88 to 99.9	462 to 856
l'Ours Cave	12 to 12.5	91 to 98	552 to 575

Table 1. Climate conditions measured in the study caves.

Following Kolar's prior archaeoacoustics fieldwork approach [8], audio source and receiver positions used in recording impulse response measurements serve as proxies for human sound-generation and auditory reception. Loudspeakers (except the ground-located subwoofer) were located in correspondence with human vocal production, at an approximate head-height (1.5m) at the level of the ear-height of the researcher wearing the in-ear (blocked meatus) binuaral microphones. The microphone arrays of analytical interest to our discussion here, two portable first-order Ambisonics (FOA) recorders (Zoom H3VR) were arranged to locate their "left-up" (channel 1) capsules as spatial proxies for in-ear binaural microphones, spaced 17cm apart in accordance with the typical interaural distance used by the ORTF coincident stereophony standard. This double-FOA "binaural" setup was proposed by Kolar for its spatial sampling accuracy as a proxy for human ear locations (head and torso/body features can be then estimated with filters), then augmented with height channels to produce the "W-Ambisonics" 3D-microphone recording technique developed and perceptually tested by Lu and Kim for multi-speaker spatial audio rendering [9].

2.3 Measurement Strategies and Locations

We chose measurement locations according to comparable and distinct physical features to collect data for quantifying and demonstrating how different geomorphological features relate to cave acoustics. In our comparison, we present the following cave contexts:

In Saint-Marcel Cave, we studied three specific locations in the same extensive gallery (known as Web 1). Two of these are located near the cave's natural entrance, while one is located in a gallery called "Les Boas". The two final locations of our study are situated in l'Ours Cave.

Location (A): Saint-Marcel Cave, "Les Boas" Gallery (Fig.1). This wide gallery is considered the archetype of all Saint-Marcel Galleries, surrounded with smooth limestone shapes. At 20m by 10m, Les Boas ("the boas") is

Figure 1. Equipment setup in "Les Boas" Gallery of Saint-Marcel Cave (Location A).

Figure 2. Equipment setup in the main gallery of l'Ours Cave (Location B).

Figure 3. Equipment setup in the speleothem-lined cavity of l'Ours Cave (Location C).

Figure 4. Equipment setup under the multi-domed ceiling of Saint-Marcel (Location E).

named after the snake-like calcite formations on its ground: sinter-pool or rimstone pool formations that run all over the gallery. Between those calcite formations, the ground is covered with clay. We located our audio equipment to make measurements somewhat equidistant from walls or pool barriers, centering both sources and receivers near the northern end yet within its large open volume.

Location (B): l'Ours Cave, main gallery (Fig.2). This gallery is a small volume, 10m by 7m, with a smooth limestone profile and ground covered with clay. We positioned both the sources and receivers about 50cm from the south wall of the gallery, in a line approximately parallel to that wall.

Location (C): l'Ours Cave, cavity (Fig.3). In this niche-like location adjacent to the main gallery in the l'Ours Cave, we positioned both sources and receivers along the center of a narrow cavity with a diameter of approximately 5m, surrounded by a great concentration of calcite speleothems.

Location (D): A single-domed ceiling area in Saint-Marcel Cave. We positioned both sources and receivers centered under this 2.5m x 2m x 1m dome.

Location (E): A multi-domed ceiling area in Saint-Marcel Cave (Fig.4). We selected this final testing location of the study due to its profile similarities with the so-called "Woman-Bison" feature of nearby Chauvet Cave, with a smooth and pocketed limestone ceiling.

3. DATA ANALYSIS AND INTERPRETATION

Prior studies of cave acoustics have been predicated on hearing echoes and noting tonal responses to the human voice, particularly in contexts of parietal art [10]. Consequently, acoustical research on caves has been preoccupied with exploring the relationship between wall paintings and notable sound effects [11] [12]. We assert there are additional sonic factors of interest. The topic of acoustical parameterization in archaeocoustics has attracted controversy since that field's earliest organized professional event at the McDonald Institute for Archaeological Research at Cambridge University, documented in the edited volume "Archaeoacoustics" by Scarre and Lawson [13]. Relating measured acoustical metrics that have been developed for documentation of the recent built environment presents considerable challenges when applied in ancient and landform contexts such as caves. Ian Cross and Aaron Watson explored this problem in the aforementioned volume, questioning, "can we use this information represented in these measurements to understand the substance of social activities involving sound in cultures and periods other than our own?" [13]:107.

Some acoustical parameters might be more relevant in cave studies than others. Here, we address the question of analytical translation across time and human contexts in terms of key metrics from the international room acoustics measurement standard ISO 3382, with the premise that cave environments are enclosed spaces whose sonic prolongation and coloration features relate to commonly noted perceptions of caves, and with the intention of relating our study to acoustics literature on caves which uses these metrics. In addition to the ubiquitous RT30 metric, we bring to attention the Early Decay Time (EDT) metric because it describes the initial acoustical energy that provides important perceptual context cues about human's immediate surroundings [14]: 27-30. For this reason, the measurements in this study were taken within the critical distance between source and receiver, in which the direct sound energy is higher than the reverberant (indirect) energy. In more comprehensive speleoacoustical surveys, we would produce measurements reflecting a greater range of distances between source and receivers.

We display our impulse response analyses using the commercial acoustical measurement software RØDE Fuzzmeasure; however, during our analyses, we also verified values using the shareware tool Room EQ Wizard, and we checked some band calculations in other software. Because each day of our 3-day case-study tested a specific combination of methodological propositions — using different equipment and configurations per day — we do not present here an equal comparison across all cave settings. Rather, we use comparative techniques to highlight observations about equipment performance, as well as our purpose in demonstrating the great variety of speleoacoustical features present in just two cave systems within the same region.

3.1 Spatial Acoustics, Equipment Performance, and Acoustical Metrics: A Web of Possibilities

We examine here the cave impulse response data collected using both mathematically generated acoustical test signals via loudspeakers and human-produced impulsive sounds. Note that we did not bandlimit the full-range test signal played through the subwoofer; therefore, its production of mid and high frequencies should be excluded from the analysis, but we graph its output to document its performance, which our study tested.

First, in a central location with a dry clay floor within a large-volume cave (Les Boas, Saint-Marcel; Location A; Fig.1) we compare the following impulse response measurement sources, recorded with an omnidirectional microphone (Behringer ECM-8000): a) a human-produced broad-band impulse (via wooden clappers); b) broad-band loudspeaker-reproduced sinesweeps through a Meyer MM-4XP single-driver loudspeaker (120Hz–18kHz) positioned at 1.5m above the ground; c) the same sinusoidal signals through a JBL BassPro SL8 subwoofer (35-120 Hz), located on the ground under the Meyer radiating in an upward hemisphere.

This experimental construct enables us to quantify the spatial response differences in produced acoustical energy between a human-produced impulse and loudspeakers with different spectral profiles. We selected the loudspeakers on the basis of their quality vs. portability features including size and power consumption. We note that the directional Meyer MM-4XP has been used extensively as a proxy for vocal and aerophone sources in our previous archaeoacoustics fieldwork [15].

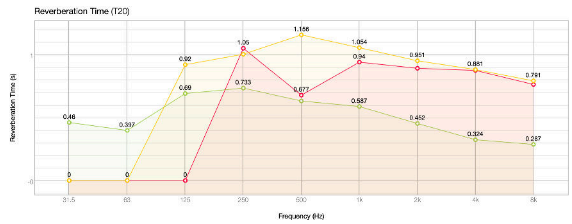

Figure 5. RT20 in two caves calculated from human-produced impulse responses from wooden clappers in Saint-Marcel (yellow & red) and l'Ours (green).

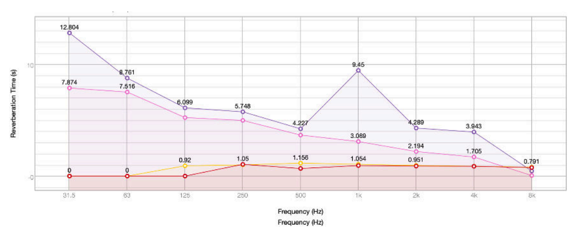

Figure 6. RT20 comparison among the sources in Les Boas gallery of Saint-Marcel cave: 2 claps (yellow & red), Meyer-MM4XP miniature loudspeaker (pink), and JBL BassPro SL8 compact subwoofer (purple). Note the excellent agreement among loudspeaker sources yet with spurious values above 500 Hz for the subwoofer, which distorts higher frequencies.

We compare in Fig.10 the above impulse response measurements to those made with the same equipment in the main central room within a small-volume cave (l'Ours; Location B, Fig.2). In l'Ours, the measurements were adjacent to a smooth, slightly pitted and somewhat curvy limestone wall, with a damp clay floor.

3.1.1 IR Measurement Analysis in Saint-Marcel Les Boas / Location (A)

Human-produced impulsive signals such as those from our wooden clappers can be particularly useful in speleoacoustics because of their portability; however, they are not reliably full-spectrum. We used them with caveats, and here evaluate their performance in different cave settings. One of the functional issues is the produced energy across the frequency spectrum, whose requirement varies depending on the dimensions of the space being measured. Comparing two human-clapped impulses using the same wooden clappers, in the same location, produced slightly different estimations of reverberation time (claps, RT20, in Fig.5, in yellow and red). We noticed a lack of low-frequency energy, and can attribute it to the source production through comparison using IRs created via a 20Hz-20kHz, 40-second sinusoidal sweep through both a subwoofer and a precision miniature loudspeaker (Fig.6). The RT20 comparison of these 3 test signal sources in Les Boas tracks well into plausible values in the lowest frequencies, around 12 seconds in the 31.5Hz-centered band, reducing

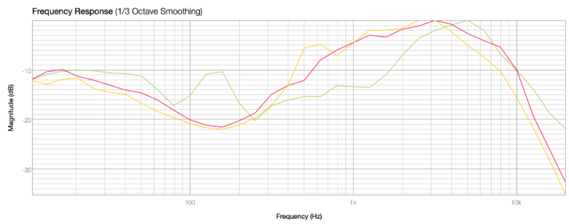

Figure 7. Normalized magnitude frequency response of three human-produced IRs with third-octave smoothing: two from Les Boas (red & yellow) and one from the much smaller l'Ours cave's main gallery (green).

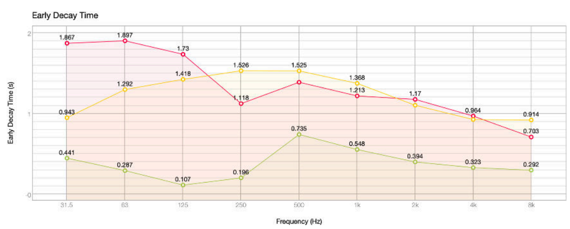

Figure 8. EDT values from two caves, calculated from human-produced impulse responses from wooden clappers in Saint-Marcel (yellow & red) and l'Ours (green).

to 4-6 seconds in the mid-range, and about half that around 1kHz (note that the 9-sec value at 1kHz for the subwoofer has been miscalculated by the software, due to distorted production in this range). For mechanical comparison, we checked the same clapper source from our measurements in l'Ours Cave, which demonstrates that the clapper is capable of producing low frequency energy (Fig.5, in green). The normalized magnitude frequency response graph of all three clapped IRs demonstrates good correspondence across the spectrum (Fig.7).

Another analytical tool for understanding the energetic profile of sound sources within the critical distance (where direct energy is higher than reverberant) is the EDT metric. For our clapped IRs in Les Boas, EDT values in low frequency bands are greater than for the RT20 metric, which corroborates our interpretation that produced low-frequency energy was very low for the clap-generated IRs in proportion to the spatial dimensions to be engergized (Fig.8). In comparing the non-normalized magnitude frequency response of the three sound source types in Les Boas (Fig.9), we verify the consistency between these two clap-produced IRs, as well as the relative greater energy in low frequencies of signals produced by the JBL subwoofer, and also the broadband regularity of the Meyer loudspeaker.

3.1.2 IR Measurement Analysis in L'Ours Cave Locations (B) and (C)

In both the compact cave system of l'Ours and in the enormous gallery of Saint-Marcel Les Boas, we used the same equipment and procedures to make acoustical measurements using both loudspeakers and human-generated impulses. (Fig.10), a graph of RT20, shows excellent agreement across sound-production methods. Based on this demonstration, and from cross-comparison across different RT calculation methods, we believe that the 4-second reverberation time in the lowest octave band is correct, as well as the generally decreasing RT/frequency towards the figure of 0.28 seconds in the 8kHz-centered band. Further, our personal perceptions of the relatively longer low-frequency reverberation in both caves is corroborated by these data. In (Fig.11) we present the magnitude frequency response of the clapped impulse (green), miniature loudspeaker (pink), and subwoofer (purple) in order to show that l'Ours cave's geomorphological profile has particular implications for high-frequency sound. Observe the trend in both clapped IR and Meyer-speaker-produced IR: an irregular and decreasing frequency response starting around 400Hz and rolling off rapidly with increasing frequency. Due to the relatively low volume of the cave, we hypothesize that this high-frequency absorptiveness is not predominantly due to distance-based air absorption – as might be the case in a voluminous cave, such as Saint-Marcel – but rather due to the many air spaces within the small-scale irregularities of its stone surfaces.

It is informative to compare two areas in the main room of l'Ours Cave, via RT30 (Fig.12) and EDT (Fig.13) values computed from clapped impulse responses recorded on only one cardioid microphone of our H3VR Ambisonics recorders. These data demonstrate the consistency in overall frequency characteristics of this room because of its relatively small size, whether the microphone receivers were adjacent to a smooth limestone wall (the red line) or closer to the center of that volume (the blue line). One of the striking features is the 50Hz room mode that is visible in the RT30 curve, because it appears as a boost in one position and a notch in the other. Similarly, there is clear modal activity at 125Hz. Both positions' high-frequency response curves are nearly identical, and we see the same trend when comparing the EDT (Fig.14) and RT30 (Fig.15) of measurements made within the adjacent speleothem-lined cavity. Of importance here is the extreme difference in frequency profiles between the early reverberation and its later development. Likely due to the rapid interactions of high frequencies with cave structures such as small cavities with calcite formations, the early re-

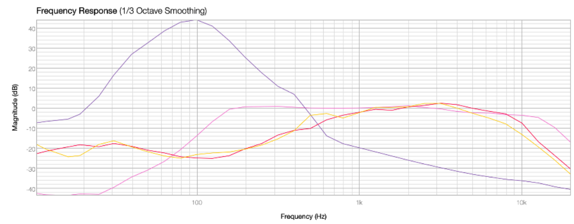

Figure 9. Les Boas sound sources – non-normalized, magnitude frequency response of the three source types, with third-octave smoothing: 2 human-produced impulses with wooden clapper (yellow & red), Meyer-MM4XP miniature loudspeaker (pink), JBL BassPro SL8 compact subwoofer (purple).

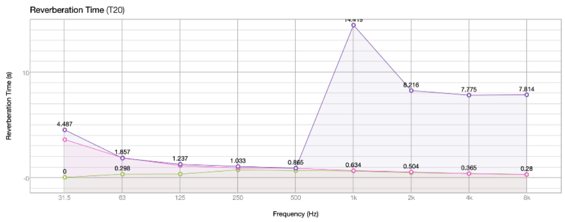

Figure 10. RT20 values from the three sound sources in l'Ours Cave's main gallery: human-produced impulse from wooden clapper (green), Meyer MM-4XP miniature loudspeaker (pink), JBL BassPro SL8 compact subwoofer (purple). Note erroneous values for the subwoofer from the distorted signal above 500Hz.

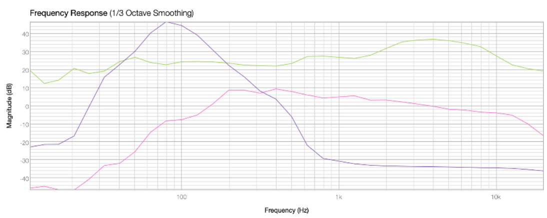

Figure 11. l'Ours sound sources – non-normalized, magnitude frequency response of the three source types, with third-octave smoothing: wooden clapper (green), Meyer MM-4XP miniature loudspeaker (pink), JBL BassPro SL8 compact subwoofer (purple).

verberation as quantified by the EDT metric is dominated by mid-frequencies, whereas over time, higher frequencies disappear and lower frequencies are prolonged according to the larger dimensions of the cave. Without attention to the time-dependencies of reverberation metrics, this particular behavior could be overlooked, with psychoacoustical implications.

3.2 "Human-Centered" Comparison of Speleoacoustical Features

The above contrasting features in cave measurement scenarios are comparable due to consistency of equipment and procedure. Fundamental to our research is the proposition that speleoacoustical measurements are best related to human experience when conducted in terms of human spatial scaling. In other words, acoustical test signals are produced where humans could make sound, with microphone receivers located in humanly plausible locations to enable spatially accurate translations of measured acoustics into auralizations and data-driven models.

Towards this goal, we cave-tested a time-code synchronized pair of Zoom H3VR first-order Ambisonics microphones (the double-FOA "binaural" setup or "double-H3VR array") in which we take the signal from only the "left-up" (channel 1) of each H3VR, positioned according to a 17-cm interaural distance to approximate binaural hearing spatial sampling, with those capsules oriented outwards as proxies for in-ear microphones. These data can

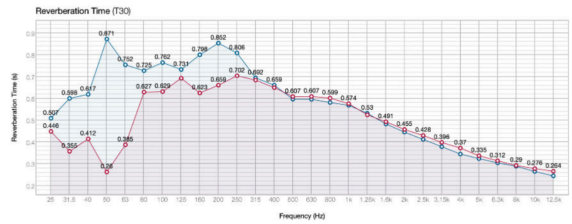

Figure 12. RT30 calculated from clapped impulse responses measured at two locations within l'Ours cave's main gallery: one at the first position, by the wall (red), and a second position more central to the larger volume, farther away from the highly variable surface of the limestone walls (blue).

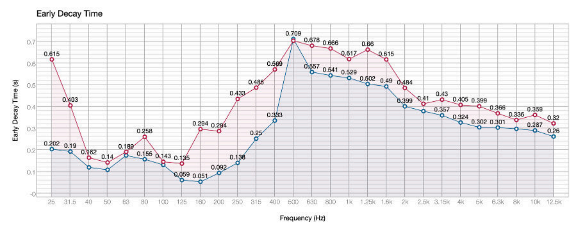

Figure 13. EDT calculated from clapped impulse responses measured at two locations within l'Ours cave's main gallery: as above in Fig.12.

be analyzed directly to estimate the differences in soundfield reception at each ear of a human listener, and both the 2-channel reduction and the 8-channel double-FOA data can be applied in the rendering of immersive binural auralizations. Via the following RT graphs, (Fig.16) and (Fig.17), we offer an overview of the great variety of speleoacoustical features with quantifiable binaural consequences that can be observed and measured even within the same gallery of a single cave system, or within geomorphologically similar caves. We have targeted specific features within the southern gallery of the large Saint-Marcel cave system, and explored some of those features in comparison with measurements from the smaller l'Ours cave.

3.3 Analytical Considerations and Future Directions

A concise preliminary study, such as we present here, that compares equipment across select locations in two caves cannot thoroughly cover all methodological premises for speleoacoustics. Of interest in our future research is the development of strategies for comprehensively exploring, documenting, and evaluating the acoustics of an entire gallery or the complex interconnectivities among spaces within an extensive cave system, such as the research we have begun in Grotte Chauvet fieldwork in March 2022. It is apparent from our initial analysis of measurements from a relatively tiny area within the voluminous space of Les Boas (which covers only about 100m within an interconnected cave system that extends for several kilometers, with large cross-sectional dimensions) that measured RT has particularly local constraints according to source fea-

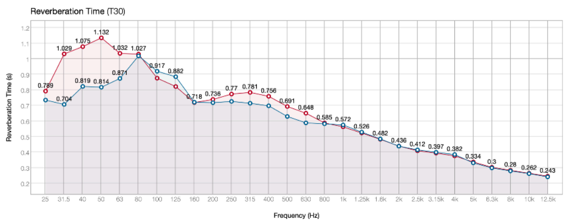

Figure 14. RT30 calculated from clapped impulse responses measured at the two, binaurally spaced outward-facing ”left-up” channels of the double-H3VR array in the speleothem-lined cavity of the l’Ours cave.

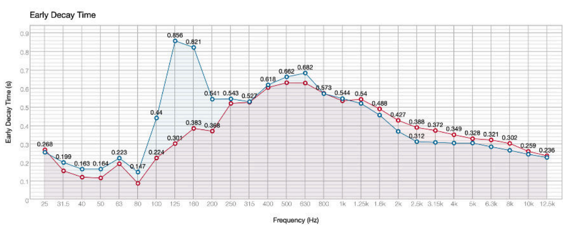

Figure 15. EDT calculated from clapped impulse responses measured as above in Fig.14.

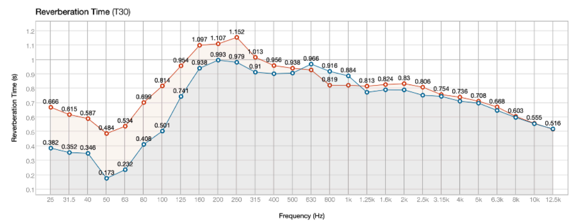

Figure 16. RT30 calculated from clapped impulse responses measured at the two, binaurally spaced outward-facing “left-up” channels of the double-H3VR array located underneath the Saint-Marcel multi-domed area pictured in Fig.4.

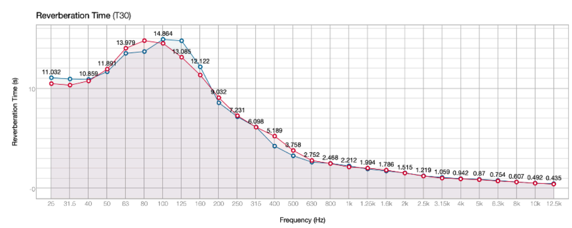

Figure 17. RT30 calculated from clapped impulse responses measured at the two, binaurally spaced outward-facing “left-up” channels of the double-H3VR array located under a small ceiling dome in a wide gallery area in the Saint-Marcel cave.

tures and particularly produced sound energy – as well as the gain structure and sampling resolution of the recording devices – in response to the physical scale of the cave setting.

Through selected examples of spatial impulse response measurements made according to locations of plausible human activity, and using human sound-producing and binaural-receiving proxy locations for sources and receivers, we have demonstrated an enormous range of acoustical contrasts that correspond with a diversity of cave features. By comparing the measurable effects of different source production and receiver locations, we show how acoustical measurement results are contingent upon contextual factors that complicate the application of standard acoustical test signals, procedures, and metrics.

4. SPELEOACOUSTICS APPLIED: AURALIZATIONS FOR MUSIC EXPERIMENTATION

We emphasize that this speleoacoustics study is a preliminary exploration to inform our future acoustical studies of Ardèche limestone caves, together and in collaboration with a cross-disciplinary team with an archaeoacoustical premise. We discuss here some considerations in building strong methodological strategies to guide us in producing accurate and extensible acoustical data with relevance to human experience in caves. Preliminary findings on the acoustics of these caves also inform rationales for new strategies to “human-center” speleoacoustical data collection. Our fieldwork here produced the first of a growing collection of speleoacoustical data to be applied in auralizations and immersive experiences, for archaeological research, music experimentation, and novel applications yet to be developed. Also, it is worth noting that detailed acoustical parameters of caves would be useful in developing realistic virtual reality models that are representative of actual caves and specific cave features.

Multi-sensory models of caves are providing new forms of access to cultural heritage spaces and their scientific explorations. Vectors for many scientific fields such as geology, hydrology, karstology, climatology, and zoology, caves are exciting places for popularizing science: for example, the French Federation of Spelunking is bringing new visitors to caves through touristic access and spelunking activities that relate to scientific knowledge. But caves are also spaces for scientific explorations of cultural heritage, increasing knowledge of human life across time via archaeology, which is visible in France in particular, regarding Paleolithic use of caves for ritual as well as more recent activites that left traces in Ardèche caves [4, 5]. To enable public access to Paleolithic cultural heritage, caves secured for conservation such as the well-known Lascaux Cave and Chauvet Cave – and the undersea Cosquer Cave, whose replica opens in June 2022 – have been partially reconstructed at scale, with masterful reproductions of their parietal art. The Chauvet and Lascaux replica caves are among the 100 most-visited tourist attractions in France, bringing visitors from around the world, and virtual visual reconstruction platforms are increasing in popularity, without attention to accurate sonic simulations. Following the idea that caves offer new opportunities for popularization and transmission of scientific and cultural knowledge, replicas and virtual models of caves would benefit from immersive, physically accurate and dynamic sonification.

Although the research area relating cave acoustics with archaeology was many years ago initiated by Reznikoff and Dauvois, recent advances in archaeoacoustics, applied responsively in cave research, can produce new forms of acoustical models and auralizations relevant to human perspectives within caves. The next step is to produce spatially contextualized reconstructions of Paleolithic music, informed by anthropological science in collaboration with skilled musicians. Indeed, we can build imaginative responses to the extensive traces of musical instruments preserved since the Paleolithic; many studies have been conducted to assemble clues and build inferences about musical practices during Paleolithic times [16]. Research on music archaeology supported by archaeoacoustics enables physically accurate virtual explorations of Paleolithic music in relationship with Paleolithic visual expressive culture. Carefully documented impulse response measurements from speleoacoustical fieldwork as discussed here enable accurate data-driven auralizations of real caves, grounding virtual explorations of Paleolithic sound environments.

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