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MEASUREMENT AND AURALIZATION OF PALEOACOUSTIC LANDSCAPES IN CHAUVET CAVE

Luna Valentin[1*] **Jonathan Abel**[1] **Jonathan Berger**[1]
Chris Chafe[1] **John Chowning**[1] **Carole Fritz**[4]
Nima Farzaneh[1] **Miriam Kolar**[1] **Romain Michon**[3]
Sara Martin[2] **Peter Svensson**[2] **Matthew Wright**[1]
[1] Center for Computer Research in Music and Acoustics (CCRMA), Stanford University, USA
[2] Dept. of Electronic Systems, Norwegian University of Science and Technology (NTNU), Norway
[3] Team Emeraude, National Inst. for Research in Digital Science and Technology (INRIA), France
[4] National Center for Scientific Research (CNRS), UMR 8220 LAMS, Sorbonne University, France

ABSTRACT

This paper introduces an ongoing study towards acoustic reconstruction and auralization of Chauvet Cave, a UNESCO World Heritage site known for its 36,000-year-old prehistoric art. We outline methodological challenges, measurement constraints, and future directions in the development of auralization frameworks, towards the ultimate goal of recreating aspects of Chauvet's Paleolithic acoustics. A key limitation is the restricted measurement area, as recordings are constrained to modern walkways, leaving large parts of the cave acoustically undocumented. Additionally, geomorphological changes over thousands of years have altered the cave's structure, affecting how sound propagates today compared to its prehistoric conditions. We discuss how these factors shape data collection and acoustical modeling, highlighting the need for predictive simulations to extend beyond direct acoustical measurements. We briefly analyze impulse responses recorded with omnidirectional and Ambisonic microphones, providing insights into reverberation, clarity, and spatial distribution of reflections. These data inform auralization models that integrate various hypothetical sound sources while acknowledging inherent uncertainties.

*_**Corresponding author**_: _luna@ccrma.stanford.edu._

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1. INTRODUCTION

Chauvet Cave, a UNESCO World Heritage site, is renowned for its extraordinary 36,000-year-old wall paintings, fire remnants, paleontological deposits, and human-made structures [1], providing invaluable insights into past human life and artistic expression. However, one crucial dimension remains largely unexplored: the cave's acoustic environment. Sound is a fundamental aspect of human experience, shaping interactions with space and influencing perception, communication, and cultural practices. Within caves, acoustics may have played a significant role in rituals [2, 3], navigation, or even practical functions. The reverberant properties of caves could have amplified vocalizations [4], music-making, or distant sounds, potentially affecting how people engaged with the space and reinforcing the idea that early humans were not only keen visual observers of their surroundings but also sensitive to their sonic qualities.

Despite its importance to human communication, sound has largely been overlooked in archaeological research, which focuses on material analyses and visible expressive culture. But, multidisciplinary research employing a _social and cultural anthropology_ approach to the

Chauvet cave is currently been carried out. More specifically, Fritz and her team have focused on investigating human interactions with and perceptions of the environment into archaeological interpretations of sites and their remains. Within this framework, sound emerges as a key factor in understanding how humans navigated and interacted with the cave. In its dim interior, auditory cues may have been just as vital as torches and portable stone lamps, influencing movement and communication. To investigate these questions, the Chauvet Paleoacoustics collaborative project, *What Did They Hear?*, was launched. This initiative brings together researchers from Stanford University (USA), Norwegian University of Science and Technology (Norway), National Inst. for Research in Digital Science and Technology (France), and National Center for Scientific Research (France). to develop innovative technologies and multimedia systems that reconstruct the cave's soundscapes, spanning from its Paleolithic uses—across thousands of years—to the present day. By recreating lost acoustic environments and giving broader access to soundscape reconstructions, the project provides new avenues for exploring questions related to human uses of the cave.

Auralization—the process of reconstructing past acoustical environments through virtual acoustics—offers a bridge between archaeology and digital heritage. This approach allows both researchers and the public to experience and analyze ancient soundscapes. Virtual reconstructions enable the testing of archaeological hypotheses about sound-related practices, while museum installations and interactive platforms make these sonic environments accessible to wider audiences. Moreover, integrating virtual acoustics into archaeological research aligns with broader efforts to preserve and interpret cultural heritage using non-invasive technologies.

In this paper, we present first results of our team's acoustical data collection, analysis, and auralizations of Chauvet Cave's acoustic environments. We detail our approach to impulse response measurements, discuss the challenges of reconstructing past soundscapes, and explore potential applications of auralizations for both research and public engagement.

2. ACOUSTICAL MEASUREMENTS

The precise documentation of the acoustical environments within Chauvet Cave necessitates an approach that is acutely sensitive to conservation requirements. Conservation protocols prohibit certain measurement techniques, such as balloon pops, due to the risk of dispersing rubber debris, and also restrict the quantity of equipment permitted within the cave. Access is constricted, both spatially, to areas traversable by designated walkways, and temporally, to the duration of the authorized fieldwork campaign, which typically spans up to one month per year and must be shared among all experts working inside the Cave. The measurement methodologies delineated below employ low-impact, portable, and self-sufficient arrays of equipment that comply with conservation protocols, whilst ensuring the collection of high-quality data. We determine our methodology conforming to established room acoustics measurement practices and ISO standards in order to document spatially detailed impulse responses at this site, which presents significant accessibility challenges. The resulting recordings form the foundation for subsequent analyses and auralizations.

2.1 Data Collection

The Paleoacoustics research team conducted fieldwork in Chauvet Cave for an aggregate of 14 days distributed across the years 2022, 2023, and 2024-new data has very recently been collected in 2025 but has not been included in this paper. Over this period, we used two primary impulse response protocols, both relying on the recording of 40-second exponential sinusoidal sweeps between carefully selected source and receiver locations. Microphones and sound sources were connected synchronously to a computer through a Zoom F8N audio interface. Each source-receiver location pair was measured 3 times for optimization. We describe below the equipment configuration and measurement process.

2.1.1 Protocol A

The initial protocol implemented for measurements in Chauvet cave was intended to provide high-fidelity impulse responses that could serve both the purpose of room-acoustics analyses and auralization reconstructions for listening. The equipment set-up was chosen to simultaneously measure an optimal number of positions with the minimum equipment possible in each of the cave areas. The chosen audio equipment was a Meyer MM-4XP miniature loudspeaker known for its relatively flat frequency response, omnidirectIonality up to around 1 kHz and increasing directivity above 1 kHz, portability, and sturdiness, and a JBL BassPro SL 8-inch compact subwoofer for covering the low frequency range. We tested these sound sources in preparatory speleoacoustics research in nearby caves [5]. For receivers, four Countryman B6 omnidirectional microphones were arranged on a coupling bar, three were aligned at 0.5m intervals and the fourth one was located beside one of the extreme microphones at 17cm spread to provide binaural spatial sampling, as demonstrated in Fig. 1. To complete our approximation of a "human-centered" perspective [6], the source and receiver heights were standardized at an approximate average human ear/mouth height of 1.5m above the walkway surface. The position of the sound source in each room was determined sometimes by areas of interest, i.e., near a high concentration of paintings, and sometimes randomly. The sound receivers were then positioned to cover as many positions around the source as possible. Fig. 2 shows all the locations measured during the 2022 and 2023 fieldwork seasons.

Figure 1. Equipment set A in Salle Hillaire.

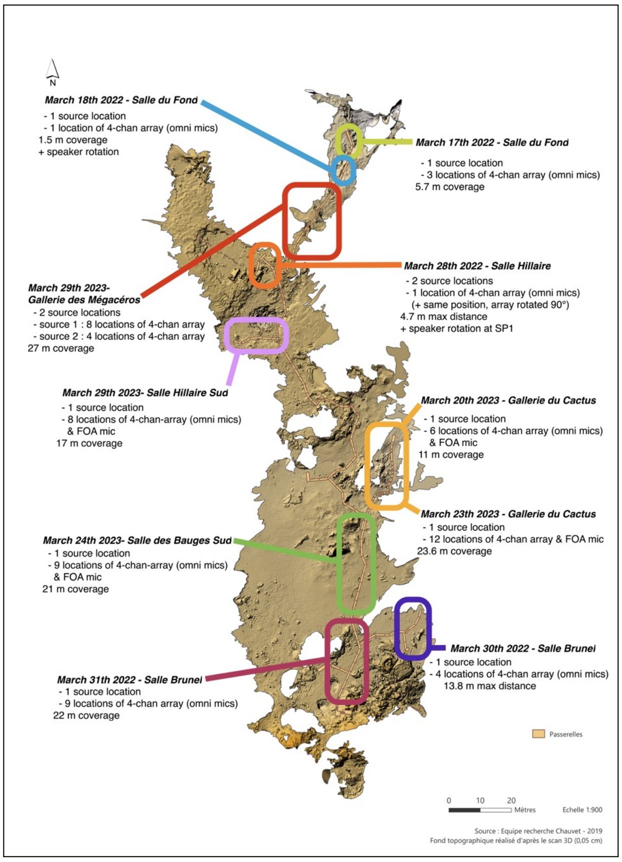

Figure 2. Map of Surveys collected with protocol A.

2.1.2 *Protocol B*

In the second protocol, the sound source and receiver were co-located to capture a representation of human auditory perception of their own sounds (footsteps, voice, etc.) within the cave's acoustic environment. The instrumentation employed comprised a Behringer HPA40 Portable sound system (featuring a 5-inch broadband speaker operable via battery, capable of producing a maximum sound pressure level of 95dB-SPL), 4 Countryman B6 omnidirectional microphones previously utilized in protocol A, as well as a Zoom H3-VR Ambisonic microphone. The height of the sound source was standardized at 1.25 meters, while the microphone array was positioned at 1.50 meters, approximating the stature of a standing human, with the vocal system (representing the mouth and chest) at 1.25 meters and the ears at 1.50 meters. The omni microphones were systematically arranged into two pairs of coupled capsules at a spacing of 17 cm, corresponding to the standard interaural distance that represents a human listener. These pairs were oriented perpendicularly to one another. In confined spaces where these dimensions were impractical, modifications were adopted and meticulously documented to accommodate the physical constraints of the environment. Subsequent to the establishment of the measurement apparatus, the sound source was rotated to angles of 90°, 180°, and 270° to acquire impulse responses across four directional orientations within the gallery or measured space and compensate the directionality of the speaker. The source and receiver locations for the acoustic impulse response measurements were predetermined prior to fieldwork to ensure a regular spatial sampling of particular locations in Chauvet cave.

Figure 3. Equipment set B in Salle Brunel.

2.2 Data Analyses

Ensuring data quality is crucial to our research where measurements are subject to environmental conditions and equipment limitations. We describe below our approach to data cleaning and the verification steps taken to ensure the reliability of our results. We also describe in this section the room acoustics parameters derived from our impulse response measurements in Chauvet Cave.

2.2.1 Measurement Equipment

The selection of measurement instruments plays a crucial role in ensuring the accuracy and reliability of acoustical data collection, particularly in challenging field conditions. The primary considerations in our selection process included portability, frequency response, and resilience to environmental factors such as humidity.

For monophonic impulse response measurements, we employed Countryman B6 microphones due to their relatively flat frequency response, omnidirectionality (their ability to capture directionally unbiased acoustic reflections), and portability, allowing us to conduct measurements efficiently in multiple locations without compromising data quality. In addition to these omnidirectional microphones, an Ambisonic microphone was required to capture directional acoustic characteristics. Several Ambisonic microphones were considered, but their performance in high-humidity environments posed a significant concern. Many available models had been previously observed to fail under extreme conditions. After evaluating different options, we selected the Zoom H3-VR, which we had previously used for acoustical measurements in cave environments with 99% relative humidity with stable operation on multiple occasions [5]. While the H3-VR's frequency response is not flat, it provides a practical balance between robustness, portability, and spatial resolution.

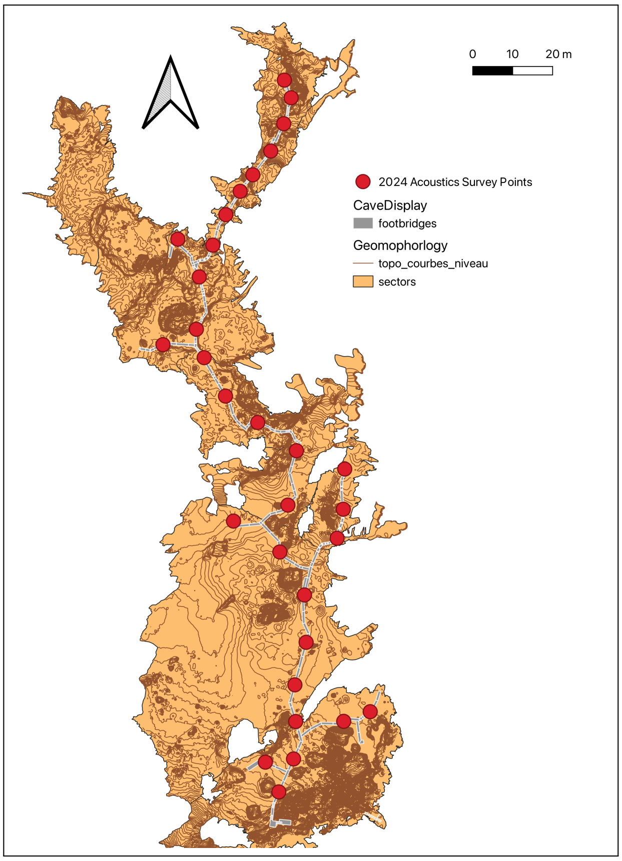

Figure 4. Map of Surveys collected with protocol B.

The choice of the excitation source is equally critical in acoustical measurements. Initially, we utilized a Meyer MM-4XP miniature loudspeaker for its great frequency response and known radiation pattern. However, given the constraints of transporting and deploying this speaker with its requisite power supply-portable battery-, we transitioned to the Behringer HPA loudspeaker, a more compact alternative with integrated battery. While its raw frequency response was observed to be less flat than that of the Meyer MM-4XP, we conducted controlled measurements in a near-anechoic studio at CCRMA, Stanford Univ., to characterize its response- within 14 dB of flat from 160 to 20000 Hz. This calibration allowed us to apply correction filters to compensate for spectral deviations, ensuring reliable excitation signals for our measurements.

2.2.2 *Quality of the Measurements*

In this section, we test whether this apparatus was clean and powerful enough to make consistent measurements. An acoustical measurement protocol's produced signal-to-noise ratio (SNR) determines how ”clean” the recorded impulse responses was, and quantifies consistency. Our target threshold was SNR $>$ 20 dB, a commonly accepted criterion for reliable acoustical measurements, since below 20 dB, relevant reverberation times cannot be extracted.

Equipment limitations can significantly affect SNR, particularly in large volumes where a more powerful sound source is required to sufficiently energize the space for accurate acoustical characterization. In such environments, inadequate excitation can lead to weak (and hence noisy) impulse responses, making it challenging to extract meaningful acoustical parameters. However, the low ambient noise conditions inside Chauvet Cave provided an advantageous measurement environment, excluding the random events of water drops. Despite the use of smaller, more portable speakers, most measurements achieved a sufficiently high SNR. Table 1 presents the statistical analysis of broadband (20Hz to 20kHz) SNR values obtained for the two distinct measurement protocols.

	Protocol A	Protocol B
# of receiver locations	264	31
Number of IRs	2652	3632
# with SNR $>$ 20 dB	2469	3581
% with SNR $>$ 20 dB	93.1	98.6
Mean SNR (dB)	31.14	28.49
Standard Dev. (dB)	10.78	5.09
Median SNR (dB)	30.79	28.05
Minimum SNR (dB)	1.11	10.15
Maximum SNR (dB)	109.10	103.78

Table 1. Statistical overview of signal-to-noise-ratio (SNR) values across the two measurement protocols. Protocol B had more IRs per location because it measured 4 directions each.

The overall consistency in SNR across these measurements, despite the variation in protocol design and speaker configuration, suggests that the combination of low environmental noise and careful calibration of excitation levels effectively mitigated potential limitations associated with the use of smaller loudspeakers.

Given the cave environment, occasional water droplets produced transient noise in the impulse response recordings, potentially distorting analysis and explaining many of the small percentage of very low SNR values (along with the proximity of colleagues passing near the measurement location within the cave). To ensure data integrity, these artifacts were visually identified through spectrogram analysis and those IRs were systematically excluded from further processing. This step was essential in maintaining a clean dataset and preventing erroneous conclusions about the characteristics of the reverberation and reflections.

Lastly, another challenge was the resonance of the metal walkway plates within the cave. Certain sections of the walkway vibrated via airborne excitation from the loudspeaker, introducing unwanted resonances into the measurements. To mitigate these effects, we managed movement and equipment placement when we noticed resonances, including repositioning of gear, padding tripods to reduce mechanical transmission of vibrations, and at times using our own weight to stabilize the walkway and dampen resonances.

2.2.3 *Room Acoustics Analyses*

Although a detailed analysis of room acoustics is beyond the scope of this paper, the results will be used towards GIS applications and archaeological interpretations. The measurements analysed here were conducted using Protocol B, adopting a human-centered perspective to assess the perceptual effects of cave acoustics. The key acoustical parameters observed are summarized in Table 2:

- RMSE (Root Mean Square Error, dB): Indicates the overall difference in frequency response of the IRs compared to the measurement system in a almost anechoic studio, with lower values reflecting less resonant modes of rooms.
- RT60 (Reverberation Time, s): Measure the time required for sound to decay by 60 dB.
- C80 (Clarity Index, dB): Assesses speech and music clarity, with higher values indicating stronger early reflections and improved intelligibility.
- D50 (Definition, %): Represents the proportion of early-arriving sound energy relative to total energy, linked to speech intelligibility.

	Mean	STD	Min	Max
RMSE in dB	13.83	1.12	10.45	15.6
RT60 in s	1.26	0.10	0.18	2.64
C80 in dB	19.83	2.99	14.53	24.84
D50 in percent	97.40	1.54	93.81	99.22

Table 2. Chauvet Cave – Room Acoustics metrics obtained with Protocol B

These parameters provide a quantitative basis for future spatial and archaeological studies, helping to contextualize the acoustical experience of past human activities in this cave. It also informed our auralization reconstructions.

3. CHALLENGES AND CONSIDERATIONS

Reconstructing the acoustics of Chauvet Cave through auralizations presents a unique set of challenges, requiring a careful balance between scientific accuracy, archaeological interpretation, and perceptual realism. These auralizations aim to recreate how sounds might have been perceived within the cave thousands of years ago, yet several constraints—ranging from acoustical measurement limitations to long-term environmental changes—affect reconstruction results.

To build meaningful and relevant auralizations, we must first acknowledge the incomplete nature of the acoustical dataset due to restricted measurement locations and geomorphological transformations over time vs. human activities at specific times and places within the cave. Furthermore, auralization itself introduces interpretative questions: What sounds should be simulated? How do we convey uncertainties? Addressing these challenges is essential for ensuring that reconstructions remain both scientifically rigorous and contextually meaningful.

3.1 Constraints on Data Accuracy

One of the primary limitations of this study is the restricted sampling area, as measurements were constrained to the designated walkways within Chauvet Cave. These walkways follow a linear path from the current entrance to the end of the cave, allowing access to major parietal art zones but excluding other significant areas. This constraint means that we lack acoustical data from inaccessible spaces, including the Paleolithic entrance, secondary parietal zones, and smaller enclosed spaces near cave walls. As a result, our understanding of sound propagation throughout the entire cave remains incomplete, as illustrated in Fig. 2 and Fig. 4, limiting the scope of analysis and auralizations. Since a key objective of this research is to create immersive and informative reconstructions for both scientific and public engagement, the current limitations on accessible measurement areas represent a major challenge. Auralizations are inherently constrained to the spaces researchers can measure, but ideally, they should extend beyond these physical limitations to reconstruct soundscapes that are no longer accessible today. To overcome these constraints, future work should explore predictive modeling and simulated measurements, leveraging computational techniques to estimate the acoustic properties of currently inaccessible areas.

3.2 Long-Term Acoustic Changes

Another key challenge in reconstructing the soundscapes of Chauvet Cave is that the acoustical measurements collected so far represent the cave's present-day state, rather than its Paleolithic conditions, which are the ultimate focus of this research. Since the initial artwork was created approximately 38,000 years ago, the cave has undergone significant geomorphological transformations, altering both its structure and surface materials. Artwork throughout the cave has been dated to different time periods, with hundreds or thousands of years between, which could correspond to significant changes in the cave's interior structures.

The most substantial change was the collapse of the original entrance opening, which occurred in two successive phases separated by thousands of years. These events dramatically altered the cave's airflow, humidity, and acoustic circulation parameters, fundamentally changing how sound propagated throughout the cave. Additionally, speleothems continued to form over millennia, including stalactites, stalagmites, and extensive calcite flowstone covering floors and walls. These formations would have altered the reflectivity, absorption, and diffusion of sound within different chambers, to different extents based on material and structural composition. While these changes are qualitatively recognized by geomorphologists, their precise acoustical contributions remain unquantified at this stage of our research. Addressing this gap is a priority for future acoustical research.

A Paleolithic 3D model of Chauvet Cave has already been estimated by geomorphologists, resulting in a 3D model that will constitute a valuable basis for acoustical reconstructions and acoustical modeling. However, a major obstacle is the lack of acoustical data on prehistoric cave materials, as these surfaces are rarely studied in architectural acoustics or computational modeling [7]. As a first step, we plan to calibrate a ray-tracing model using the current cave geometries and measured impulse responses to ensure consistency. Once a validated current-state acoustical model of the cave is established, our next research phase will involve replacing the geometry with the estimated Paleolithic model(s) and assigning appropriate material properties to cave surfaces.

This multi-step reconstruction process could take several years, and until our models are refined and their assumptions verified, auralization frameworks must explicitly state that they are based on current cave acoustics. Clear communication of modeling premises and limitations is essential to ensure that future interpretations of prehistoric soundscapes remain grounded in scientific evidence while acknowledging the uncertainties inherent in reconstructing ancient acoustics.

3.3 Auralization Realism

Auralization serves as a tool to immerse listeners in a reconstructed sonic environment, here providing experiential insights into how Chauvet Cave may have sounded during the Upper Paleolithic. However, the challenge lies in determining what sounds should be auralized and how to communicate the contingencies of these reconstructions. Given the limited evidence regarding prehistoric human sound production and social contexts, any auralization must be understood as a combination of scientific modeling and informed speculation.

One approach to reconstructing archaeologically appropriate soundscapes is to auralize reconstructions of known Paleolithic musical instruments [8]. Flutes from this period, such as those crafted from bird bones [9], have been recovered in caves, offering a tangible reference for musical possibilities. However, beyond these flutes, it is reasonable to assume that humans engaged in singing and percussive soundmaking activities, whether through hand clapping, drumming on natural surfaces, or striking resonant objects. Additionally, the sounds of fire, used for heat, lighting, or ritual purposes, likely contributed to the cave's acoustic environment, producing crackling flames that interacted with the cave's reverberation. Beyond human-generated sounds, Chauvet Cave was at times inhabited by cave bears, an essential aspect to consider in auralizations. The vocalizations of these animals constituted a component of the cave's soundscape, despite the likelihood that our Paleolithic ancestors were not privy to these sounds—human occupancy of the cave alternated with that of the bears, and no evidence of encounters has been documented. To represent this, we propose auralizing reconstructed cave bear vocalizations [10] alongside human-produced sounds.

Despite these efforts, it is crucial to recognize the significant uncertainties in how sound was produced and experienced by humans during the Upper Paleolithic. We do not know how sound-producing instruments were played, what scales, rhythms, or techniques Paleolithic people may have used, or even whether musical practices remained consistent over the thousands of years during which Chauvet's art was created. (In fact, we don't know for sure if people engaged in musical activities in Chauvet Cave.) Our auralization reconstructions thus present hypotheses and sound samples based on reasonable assumptions about what could have been heard by humans in Chauvet Cave during its prehistoric use periods. Ultimately, archaeological auralizations will always contain speculative elements, as we will never achieve a fully accurate recreation of any prehistorical soundscape. However, by clearly acknowledging these uncertainties and methodological limitations, we ensure that the auralizations remain a thought-provoking tool for research, education, and public engagement, offering a bridge between scientific analysis and experiential interpretation of Chauvet Cave's prehistoric acoustics.

4. AURALIZATION FRAMEWORKS EXPLORED

Auralization serves as a bridge between empirical data and experiential interpretation, allowing researchers, educators, and the broader public to engage with the cave's acoustics in an immersive way. Various methodologies can be employed, ranging from direct convolution with measured impulse responses to room acoustics modeling approaches that integrate predictive simulations. Each method comes with its own assumptions, limitations, and potentials for archaeological interpretation. This section outlines the different auralization techniques explored so far in this project, including their implementation, challenges, and relevance to the study of prehistoric soundscapes.

4.1 Convolution-based Auralization

The first auralization approach employed in this study involves direct convolution of recorded impulse responses with audio sources. This technique allows us to simulate the acoustic environment by applying the cave's measured reverberation to dry audio signals, providing a perceptual experience of how sounds may have been heard within different areas of Chauvet Cave. One example of this approach is the auralization of fire sounds in four distinct locations of the cave, accessible online. These simulations offer stereo spatial cues, which can be further extended to binaural or ambisonic rendering. While this method has minimal computational requirements, making it a straightforward and efficient technique, it lacks real-time user interaction, as sound source and listener positions are fixed.

To introduce greater interactivity, we developed a web-based real-time convolution platform, available on the Chauvet PaleoAcoustics website. This platform allows users to generate and experience sounds in different rooms of the cave, offering a more flexible exploration of the acoustics. However, it operates with stereo impulse responses, meaning sound directivity and spatial localization are not preserved.

At CCRMA, we have also explored the use of impulse responses with the CAVIAR system [11], adaptable software that performs real-time multichannel convolution and feedback cancellation. This installed system provides a highly accurate spatial rendering of the cave's acoustics, allowing its audience to interact with the space by generating sounds that are then processed in real-time through the measured impulse responses. Hanging microphones enable direct input of audience-generated sounds, creating a fully immersive auditory experience thanks to distributed arrays of speakers surrounding people within. Similar to previous methods, this system renders auralizations based on specific source-receiver locations within the cave. Although one can experience one source-receiver location, movements within the cave are not enabled.

These convolution-based approaches serve as a foundational step in auralization, enabling both static and interactive explorations of Chauvet Cave's reconstructed acoustics. While computationally efficient, the simulated acoustics remain constrained to that of measured locations.

4.2 VR Experimentation

To overcome the limitation of only being able to experience auralizations at specific measured locations, we have begun implementing virtual reality (VR) environments that integrate spatialized acoustic simulations alongside a photogrammetric 3D model of the cave. This approach combines both the acoustical and visual dimensions, offering a more immersive and intuitive exploration of the cave's soundscape, with a video preview available online.

Our VR implementation is based on a photogrammetric model of the Salle du Fond (the final accessible area of Chauvet Cave), provided by the *Humanités Numériques* team. To allocate more computational power to real-time acoustic rendering, we reduced the resolution of the 3D model while maintaining sufficient detail for visual realism. The acoustical dataset is derived from a secondary protocol, not described earlier: acoustic impulse responses recorded with a reduced equipment configuration: a Meyer MM-4XP miniature loudspeaker as the sound source and a Zoom H3-VR Ambisonic microphone as the receiver. From these measurements, we constructed a point cloud of IR locations, encoding them in AmbiX (SN3D normalization) format for Ambisonic reproduction.

Currently, sound sources remain fixed, but the individual participant of the VR auralization can experience accurate spatialization via head-tracking. To enhance realism, we developed a crossfading system that enables smooth transitions between 2 listening positions [12]. At present, the system interpolates between the two closest measured IRs, using a power-preserving crossfade function to weight their contributions based on the participant's position. In the near future, we plan to extend this approach to three IRs, enabling 2D movement across a broader listening area and improving the spatial continuity of the auralization.

A key future development will be the integration of participant-generated sounds, allowing real-time interaction with the cave's reconstructed acoustics. Enabling microphone input and real-time convolution will allow users to speak, sing, or generate other sounds within the virtual environment. This feature will be made possible by leveraging co-located source and receiver measurements obtained using Protocol B, ensuring realistic and responsive acoustic rendering. So far, the VR auralization has been demonstrated using a highly speculative musical creation, yet based on hypotheses supported by a convergence of archaeological evidence. The rationale for creative choices behind this musical sample are describe in a previous paper [12]. We now aim to expand the available sound sources to allow users to choose between our music sample, a reconstructed cave-bear vocalization, and a fire recording. Additionally, we will continue collaborating with the Chauvet photogrammetry team to further optimize computational efficiency, ensuring that the VR platform remains both accurate and accessible for future research and public engagement.

4.3 Museum and Public Outreach Applications

A museum exhibition focused on Chauvet Cave's archaeological research premiered in October 2024 at the Cité des Sciences et de l'Industrie in Paris. As part of this exhibition, an archaeoacoustics module was introduced, allowing visitors to engage with the cave acoustics research and auralizations Designed as a low-tech, low-noise system per the museum's requirements, the module consists of a tablet with two headsets as can be seen Fig. 5, guiding users through interactive auditory experiences. The activities are structured to gradually introduce visitors to acoustic principles and the research process:

Figure 5. Museum's archaeoacoustics module

1. Binaural Experience: A binaural recording of a researcher moving through the cave, setting up the idea that visitors are hearing the present-day acoustics of Chauvet Cave.
2. Voice Convolution Activity: Visitors record a sample of their own voice, which is then convolved with impulse responses from one of three cave areas—Galerie du Cactus, Salle des Bauges, or Galerie des Mégacéros—allowing them to experience their voice in these different environments. To minimize loud noises in the exhibition space, prerecording was used instead of live interaction.
3. Sound Guessing Activity: Visitors listen to auralized sounds of a fire, a bear, or human footsteps, then attempt to identify in which cave areathe sound is being auralized. The three auralized cave areas have distinct geomorphological characteristics, and accompanying photos and descriptions provide insights into how cave structures influence their acoustics.
4. Distance-Based Auralization: This activity explores how sound changes with distance. Visitors hear sounds from 2m, 10m, and 20m in each cave area, illustrating the effects of sound propagation in different acoustical spaces.

The public response to these activities was very positive, with visitors finding the interactive format both engaging and educational. The inclusion of text-based explanations alongside the activities successfully conveyed the idea that this is an ongoing research project, and that current auralizations are based on the present-day acoustics of the cave. This exhibition represents an important step in bringing archaeoacoustics research to a broader audience, allowing the public to experience and reflect on the role of sound in prehistorical environments.

5. FUTURE AVENUES

The next steps in this project aim to refine acoustical modeling and auralization frameworks, addressing both scientific and public engagement goals. A primary objective is to reconstruct the acoustic environment of Chauvet Cave as it existed 36,000 years ago, incorporating a full topographical model that accounts for geomorphological changes such as the collapse of the original entrance and the evolution of speleothem formations. This will require predictive acoustic simulations based on reconstructed geometry and material properties, improving the accuracy of auralizations beyond present-day conditions.

In exploring the role of acoustics in past uses of Chauvet Cave, we also aim to engage with broader anthropological questions concerning how sound may have shaped human experiences in the cave. A recurring hypothesis in the literature on painted caves is that acoustical properties could have influenced the placement of artworks—a proposition explored in studies of sites such as Niaux and others [CITATIONS HERE]. While our current data do not suggest a direct correlation between sound properties and the location of paintings in Chauvet, we nonetheless consider it important to situate our work within this scholarly context. Rather than assuming a causal relationship, our objective is to investigate how acoustics might have interacted with the scenographic arrangement of panels and the performative or oral practices that may have occurred in these spaces. GIS (Geographic Information Systems) will support this exploration by enabling the integration of spatial and acoustic data to identify potential patterns or zones of acoustical interest. This approach does not presuppose that acoustics dictated the placement of artworks, but rather examines whether acoustical features may have contributed to how certain areas were used during rituals or communication.

Additionally, research efforts will focus on expanding and improving auralization platforms, making them more interactive and accessible. This includes enhancing VR environments with real-time participant-generated sound inputs and improving spatial interpolation techniques for more seamless acoustic transitions. Web-based and museum installations will also continue to evolve, allowing broader audiences to engage with prehistoric soundscapes in a scientifically grounded yet immersive way.

6. ACKNOWLEDGMENTS

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