Acoustics in Music Archaeology: Re-Sounding the Marsoulas Conch and Its Cave

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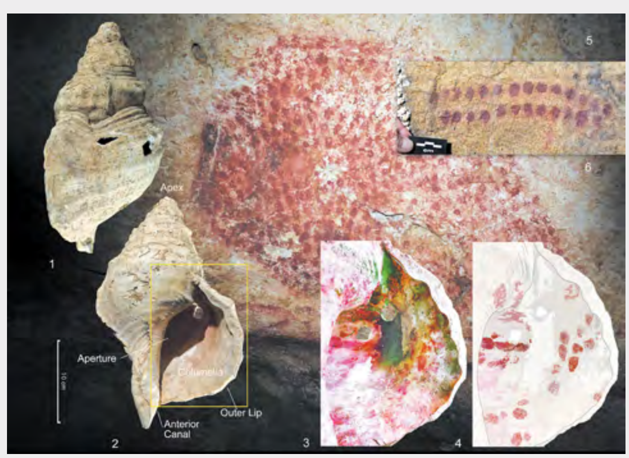
What can be learned from the sounding of a conch shell after it has been silent for 18,000 years? During the last ice age in what is now southern France, a person or people from the Magdalenian period (see bit.ly/3uCjlMc) procured a giant conch (*Charonia lampas*) (**Figure 1**) from the Atlantic Ocean and transported it more than 240 km (150 miles) to a narrow cave in the Pyrenean foothills (Haute-Garonne, France). This elaborately decorated limestone cave, known as Marsoulas (**Figure 2**), extends from its small opening like a long narrow corridor with a triangular cross section, proportions distinct from the voluminous caves typically known for Upper Paleolithic art.

The large seashell, which functions as a natural horn, bears evidence of several modifications by humans (Fritz et al., 2021). Other finds in the cave include hematite rocks and tools that may have been used to produce the red pigment adorning both the cave and the interior of the seashell. This is a rare archaeological assemblage of materials that directly link expressive visual culture with human soundmaking in the Upper Paleolithic.

Music Archaeology's Premise: Instruments, People, and Places Make Context

Music archaeology grapples with the challenge of recovering clues about purposeful soundmaking by humans in contexts distinct from those today. Thousands of years before written language, although at the same time as graphical artworks such as wall paintings, engravings, and sculptures, humans made music as evinced by the discovery of 35,000-year-old bone flutes discovered in caves of the Swabian Jura from the Aurignacian period (see bit.ly/3ITVDQC). Musical instruments are considered the most specific form of archaeological evidence for humans' nonverbal sonic expression. Therefore, musical acoustics research can aid in evaluating sounds that archaeologically evidenced instruments could make. However, explorations of instrument acoustics alone cannot reconstruct ancient music; the places where music was made are indicators about many aspects of musical behaviors as well as experiences that can be related to spatial acoustics. Instruments, people,

Figure 1. *Archaeologically excavated marine shell of* Charonia lampas *from the Marsoulas Cave (Haute-Garonne, France).* ***1*** *(**Top left**): side view.* ***2*** *(**Bottom left**): front view with the anatomical areas indicated.* ***3*** *(**Bottom center**): vestiges of red pigment (image enhanced with Dstretch software).* ***4*** *(**Bottom right**): tracing of the red dots and lines that are visible on the enhanced photo. Very similar red dots, produced with the fingertips, are present on the walls of the Marsoulas Cave.* ***5*** *(**Top center**): set of red dots forming a bison silhouette (length, 1.10 m).* ***6*** *(**Top right**): geometric sign formed by a double line of dots (shown with a centimeter scale). Photos 1, 2, 3, 5, and 6 from C. Fritz; drawing 4 from G. Tosello.* ***Figure 1*** *previously published in Fritz et al. (2021, Figure 1).*



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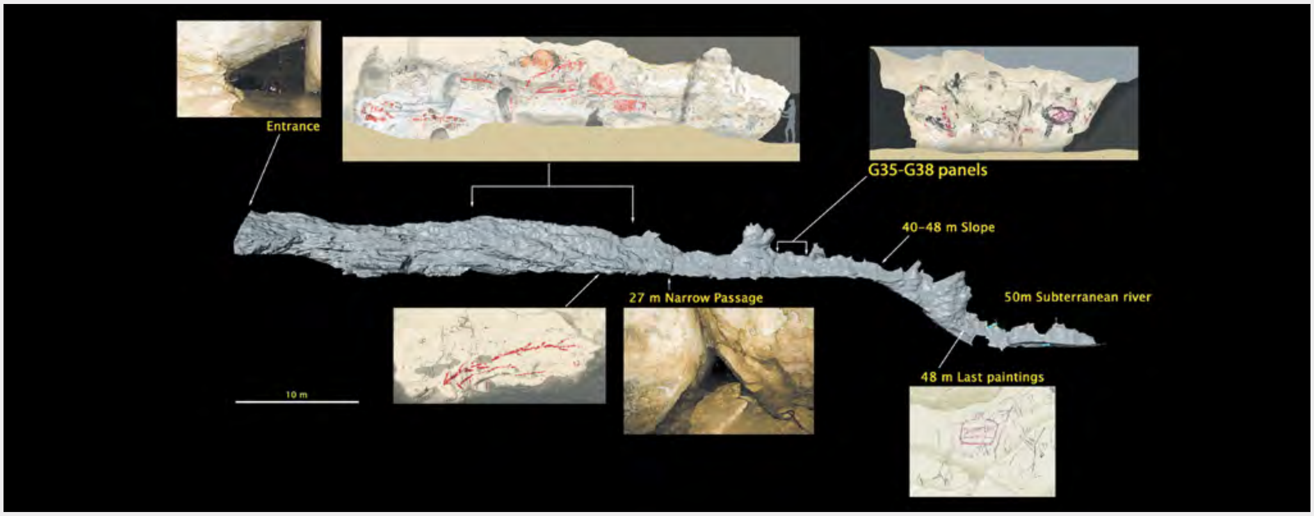


Figure 2. *Three-dimensional (3D) profile of the Marsoulas Cave from the entrance to the end (**gray area**). The decorated sections known as panels G35-G38 are presented as examples of the visual reconstructive methodology (Fritz et al., 2016). Note the cave's triangular cross-section (**top left**), and the location of its central bison panel, the site of preliminary acoustical measurements. **Figure 2** previously published in Fritz et al. (2016, Figure 1).*

and places together create the musical context explored in archaeological interpretations.

Archaeology must produce inferences regarding past human lives via remnant materials (see tinyurl.com/2a6te2m2), whereas acoustical science provides a physical basis for exploring those materials in terms of their production and transformation of sound. Acoustics and auditory science can be joined with archaeological methods to reconstruct aspects of sonic communication by humans in past settings (Kolar, 2018). Although musical instrument acoustics have been applied in many archaeological studies, less attention has been given to spatial acoustics of archaeological sites that are not known as musical or theatrical venues, such as the decorated cave where the Marsoulas conch was recovered in 1931. At that point, the conch was catalogued as a drinking vessel or ritual cup.

As an example of the utility of acoustical methods in exploring an archaeological context with musical evidence, this article highlights the study of the Marsoulas conch horn and its cave. The antiquity of Upper Paleolithic sites such as the Marsoulas cave, many of which are noted for their wall art, requires the broadest definition of music as nonverbal soundmaking by humans. The comparison of the visual artworks in this cave with techniques used to decorate the sound-producing conch that was found inside the cave demonstrate a symbolical connection between the instrument and place. In both the wall art and the shell modifications, there is pattern replication, evidence of compositional strategies, and exploration of forms from nature. To decorate the cave and the conch, humans were using visual expressive techniques that parallel those employed in historical and present-day art making; whether Paleolithic people also extended such media manipulation strategies to sonic expression is unknowable, yet is a topic to be approached through a cognitive archaeological framework. However, there is much information about past music making that can be explored through acoustical science, which provides the tools for evaluating instrument performance features, contextual manipulation, and physical interactions between sound producers and performance settings.

Music Archaeology's Acoustical Expansion

A field once focused on the identification of sound-producing instruments from archaeological materials (Eichmann, 2018), music archaeology now employs acoustics, following a larger trend in archaeology to integrate scientific methods from fields appropriate to the materials or topics being investigated (Johnson, 2020). Musical acoustics has gained recognition as the archaeometrical approach to characterizing ancient and historical sound-producing instruments, such as techniques employed to reconstruct the Deskford carnyx, a 2,000-year-old

Celtic brass sculpture as well as a lip-reed aerophone (see tinyurl.com/2adkpap3) (Campbell and Kenny, 2012).

Beyond musical instrument acoustics, a variety of acoustical research areas are being pursued in music archaeology. Spatial and architectural acoustical methods enable the exploration of interconnections between instruments and sites of their excavation or documented use, such as in the musical instrument-supported acoustical survey of the central platform and plaza at the Inca administrative city Huánco Pampa (see rogeratwood.com/article/inca-power-politics) (Kolar et al., 2018). Along with a standard spatial acoustics test signal, that study employed human-produced sounds with archaeologically appropriate instruments (a conch shell horn, a whistle, and human voice) repeated to account for performance variations. Although necessary in connecting physical acoustics with their human perceptual implications, the auditory sciences are infrequently applied, with notable exceptions such as a recent multimodal study of flintknapping (Smith, 2020) in which acoustic feedback was considered a feature in the crafting of stone tools.

Studies of performance mechanics further refine archaeological interpretations about sound-producing instruments. Much attention has been given to the contentious topic of whether certain bones found in Paleolithic archaeological contexts may have been flutes; biologist and flautist Jelle Atema has conducted detailed experiments in both instrument production and performance to recommend nuanced criteria for the evaluation of proposed sound-producing instruments (Atema, 2014). When performance explorations are connected anthropologically, as in the archaeo-ethnomusicological study of Andean music by Olsen (2002), reconstructive hypotheses can be evaluated in terms of known practices across cultures. Musical acoustics methods enable the reevaluation of archaeological classifications previously made without physical explorations to revise functional hypotheses, as in the study of sucked trumpets across prehistoric Europe and North America (Rainio, 2016). Thus, it becomes clear that acoustics and auditory science offer a range of theoretical and experimental tools to inform music archaeology's expanding terrain (Stöckli and Howell, 2020).

Whereas research in musical instrument acoustics (see newt.phys.unsw.edu.au/music) aids in the mechanical evaluation and description of archaeological objects that can produce sound (Wolfe, 2018; Campbell, 2021), research on spatial acoustics is equally important in characterizing the settings for past music making and musical perception. Architecture can be sound enhancing, such as the temple of Kukulkán (ca 1050-1300 CE) at Chichén Itzá (see tinyurl.com/2s3pynke) (Lubman, 1998). Buildings and structures can also be sound producing, such as the pre-Hispanic "sprung dance floor" in the site of Viejo Sangayaico (ca 1000-1615 CE) in southeastern Perú (Lane, In Press). Reconstructions of place-based musical practices present opportunities to study sound-makers in context, such as research on conch shell horns at Chaco Canyon (see whc.unesco.org/en/list/353) in the North American southwest (Loose, 2012) and in recent aerophone reconstructions from the first-millennium metropolis of Teotihuacan near Mexico City (see whc.unesco.org/en/list/414) (Both, 2021).

Acoustic interactions between sound-producing instruments and both built and natural structures provide clues to identify and characterize past human musical activities and experiences of particular places. For example, the study of two early-twentieth century carillons in Toronto, Ontario, Canada (see acousticstoday.org/heritage-carillons) explored "the instrument and its context...holistically, more accurately reflecting the musical sensitivity of a carillonist" by "spectral analysis of audio samples of each bell at different musical dynamic levels [that] enabled the analysis of the acoustic qualities of the bells and the mechanical action of the instruments" (Orr, 2021, p. 1). Orr's in situ research detailed the instrument-building interactions that influence performance practices as well as audience perceptions. The cross-comparison of spatial and instrument acoustics can suggest ritual functions, as in the study of conch shell horns in the enigmatic first millennium BCE stone architecture of Chavín de Huántar, Perú (see whc.unesco.org/en/list/330), where parallel ducts filter and project the fundamental tones of these instruments between a hidden carved monolith and a countersunk plaza that is decorated with relief carvings of conch shell horn performers (see tinyurl.com/yacxey3d) (Kolar et al., 2012).

Acoustical Music Archaeology: Investigating the Marsoulas Conch and Its Cave

Studying how the Marsoulas conch sounds and the ways its sound can be transformed within the painted cave where it was discovered reveals physical parameters about ancient music in a site that was previously only renowned for its elaborate visual artwork. In the cave, around 500 motifs, including geometric markings and more than 340 paintings of animal and human figures both engraved and painted in red (hematite) and black (charcoal), cover the short walls of a limestone corridor long ago carved out by water. "The art of Marsoulas is of profound stylistic originality with few equivalents in the region from the same period" including naturalistic horses, bison, and other horned animals (Fritz et al., 2016).

Marsoulas cave's small cross section is a physical constraint for both visual and musical expressive activities within the cave that guides hypotheses about possible social configurations, limiting where and how many people could have engaged with the art and acoustics. For example, it could be practical to project the sound of the powerful conch shell along the median axis of 100 meters (328 feet), yet even a few people within the cave could dampen the sound, as demonstrated in performance tests.

The first step in a music archaeological investigation is questioning the musical premise. Only recently was the Marsoulas conch identified as a possible sound-producing instrument, nearly a century after its archaeological recovery. Initial research on the seashell documented its physical and acoustical features and presented physical evidence for its modification and use as a tool for sonic expression (Fritz et al., 2021). The investigators' approach to the Marsoulas conch included characterizing human modifications to the shell that include strike marks around its lip, an opened spire, and a mysterious circular perforation that may have pierced the external spire and extends through two turns of the horn inside (Fritz et al., 2021). Performance acoustics were explored at the Maison des Sciences de l'Homme in Toulouse, France (MSHS-T) where a musicologist and horn player performed the seashell as a lip-valve "natural horn." The performance of the artifact shell produced sounding tones of fundamental frequencies at 256, 265, and 285 Hz, with harmonics typical of such instruments having a conical bore (interior cavity) (Wolfe, 2020).

To corroborate their experimental verification of the seashell as a sound-producing instrument, the investigators sought ethnographical analogies for similarly modified shells, which sometimes have external mouthpiece modifications and additions, as shown in **Figure 3**, *right panel*, 6-10.

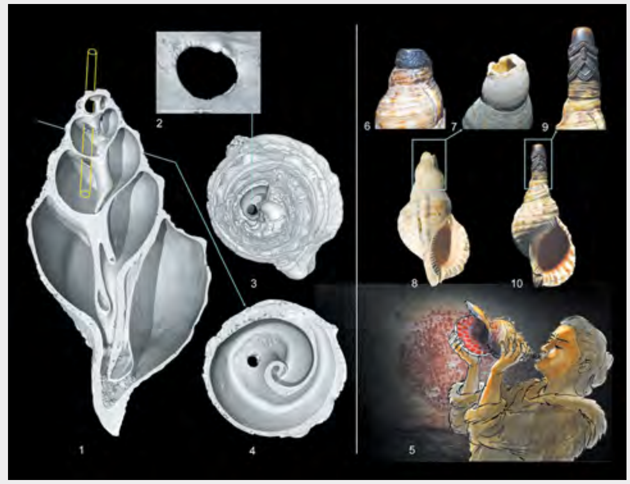


Figure 3. *The* Charonia *wind instrument.* ***Left panel: 1 (left)****: sagittal section of the 3D model of the shell that makes it possible to visualize the hole drilled at the level of the sixth spire.* ***2 (Top right)****: detail of the circular perforation drilled from the apex. The streaks on the edge are due to a skidding tool.* ***3 (Middle right)****: top view of the 3D model showing the perforation.* ***4 (Bottom right)****: 3D cross section at the level of the seventh spire.* ***5****: (****Bottom right****): the conch of Marsoulas in its Magdalenian context (hypothetical restitution).* ***6****: (****Top left****): conch from Southeast Asia, the mouth of which is covered with a black coating, intended to protect the lips of the blower.* ***7*** *and* ***8****: Conch from Syria (****left middle****) and detail of its chipped mouth (****top middle****), close to that of Marsoulas.* ***9*** *and* ***10****: Conch from New Zealand (****middle right****) and its mouthpiece made of a decorated bone tube (****top right****). 3D model captures 1 to 4 from C. Fritz; drawing 5 from G. Tosello; photos 6 to 10 from E. Kasarhérou, Musée du Quai Branly-Jacques Chirac, Paris, France.* ***Figure 3*** *previously published in Fritz et al. (2021, Figure 3).*

Despite the Marsoulas conch's compliance in tonal sound production, its researcher-performer noted its jagged and uncomfortable mouthpiece, which bears evidence of prior application of "a thin layer of a brownish colored material preserved on the outside and inside of the apex" (Fritz et al., 2021, p. 1) that is hypothesized as a substance used either to smooth the mouthpiece or to affix an attachment. Curiously, even with its pointy spire removed as required to create a natural mouthpiece, the Marsoulas conch was perforated by a 1-centimeter-diameter circular hole bored through two turns of its coiled conical interior, enabling the insertion of a narrow tube as illustrated in **Figure 3**. Although these aligned circular perforations can function to stabilize an inserted tube, their diameter is much smaller than would be appropriate for an externally affixed mouthpiece, a consideration not explored in the initial study.

Due to the age and fragility of the Marsoulas conch, two resin replicas were commissioned, including the application of pigments to replicate those inside the archaeological shell. In September 2021, we compared the Marsoulas conch with its resin replicas in the Museum of Toulouse. The two resin replica horns produced tones with central frequencies comparable to those of the ancient seashell, verifying their suitability as experimental proxies. We then traveled to several caves in southern France for performance tests using one of the replica conch horns in associated archaeological settings, including a brief visit to the Marsoulas Cave where we made spatial acoustical impulse-response measurements and documented performance tests with the replica instrument. The long and narrow cave has been laser scanned and its extensive artworks investigated using customized image-processing techniques that allow production analyses and multimedia reconstructions (Fritz and Tosello, 2010), as shown in **Figure 2** (Fritz et al., 2016).

The reunion of the Marsoulas conch, in the form of its functionally equal resin replica within its excavation context, the Marsoulas Cave, enabled observations about musical plausibilities in a site of the shell horn's likely ancient sounding. Performance experiments can identify contextual sound effects, and they enable the description of site acoustical features that can be measured and expressed according to standard procedures and metrics. Both outside and inside Marsoulas cave, the sounding tone of the replica conch horn was measured from 258 to 260 Hz, within expected range of variation around the 256-Hz fundamental frequency documented in the shell horn's acoustical study (Fritz et al., 2021). We first performed the replica horn on the edge of the ravine outside the opening of the cave into the adjacent valley below (**Figure 4**), from where we heard and recorded converging echoes that prolonged the instrument's sounding tone for almost four seconds. In performance tests inside the cave, we documented frequencies produced using the downward pitch-bending technique in which the player's hand is partially inserted into the shell lip, or musical instrument bell, effectively lengthening its bore (Campbell et al., 2021). With the replica conch, the performer could "bend the tone down" to 234 Hz, extending the shell horn's frequency range. Although to observers, sounds from the replica conch horn did seem to "fill the cave," its performance did not notably excite spatial acoustical modes as we have observed in archaeoacoustics research with shell horns in architectural settings of similar dimensions, such as the stone galleries of Chavín de Huántar, Perú (see tinyurl.com/yckmef63) (Kolar, 2019).

Figure 5. *Experimental setup for acoustical impulse-response measurements in the central section of the Marsoulas Cave, adjacent to its iconic, red-dotted bison image (**right**). A portable omnidirectional loudspeaker and spatial audio recorder were used in this fieldwork conducted by Kolar, Nerness and Valentin in September 2021. Photo by Barbara Nerness.*

Figure 4. *A music archaeology experimental study just outside the Marsoulas Cave using a 3D-printed and hand-painted replica of the Marsoulas conch. Performed here by auralization researcher Romain Michon. Photo by Barbara Nerness.*

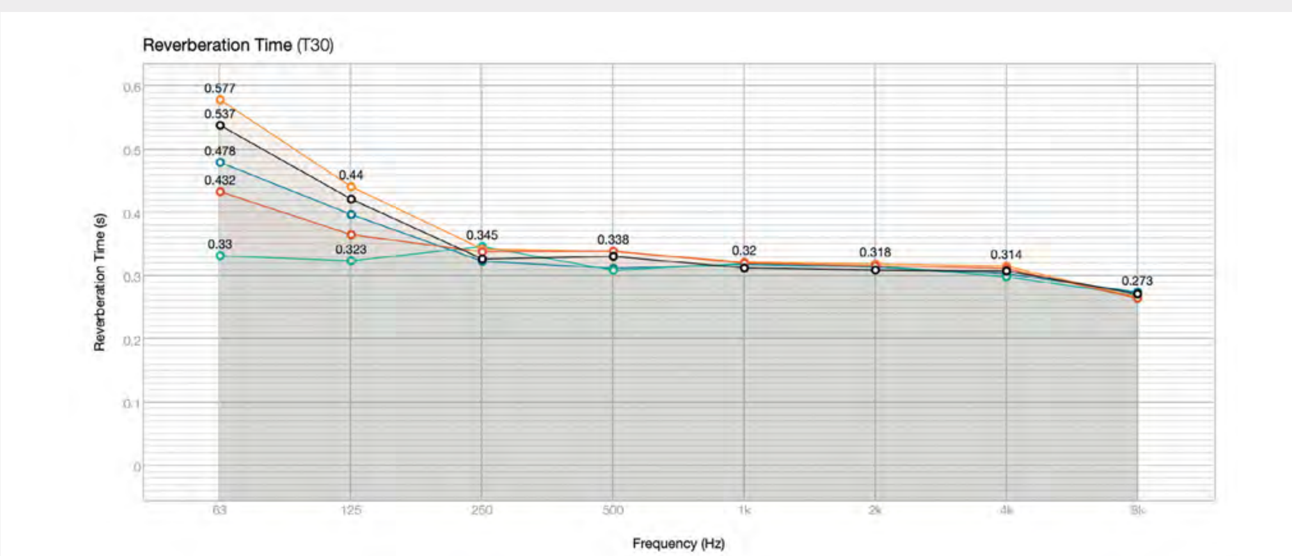
Characterization of how the Marsoulas Cave modifies sounds produced within was done using portable audio electronics (**Figure 5**) to make spatial impulse-response measurements. This is the standard procedure for room acoustics, where a known signal is produced from a source and recorded by microphone receivers for analysis. The sound source and receiver were located at approximate human head heights in various positions within the central section of the cave. Due to prior excavations and the presence of a few metal support structures, there cannot be perfect correspondence between the extant cave interior and its conditions during Magdalenian times. However, the overall dimensions and cross-sectional geometries of the cave have not been modified (as evinced by the intact paintings); therefore, measured acoustical parameters and noted structural features would have been similar during the Upper Paleolithic.

Impulse-response measurements are the standard technique for documenting how an enclosed space reflects and absorbs acoustic energy throughout the frequency spectrum of human audition and bodily sensing. One of the most common acoustical metrics for enclosed spaces that has strong perceptual implications is reverberation time. In the Marsoulas Cave, an analysis of spatial impulse responses collected in locations near the wall art indicate short reverberation times across most of the range of human hearing, around 300 milliseconds for octave bands centered at 250 Hz (near the Marsoulas conch's sounding tone) and above. The standard RT30 metric for reverberation time (**Figure 6**) shows an increase in the prolongation of sound with decreasing frequency, reaching about a half-second duration in the 63-Hz centered band, below that produced by the conch and consistent with the cave's length. Measured acoustics enable the tuning and verification of computational acoustical models, a new research direction that will be used to produce auralization demonstrations of the conch in its cave.

Musical Acoustics for Archaeological Interpretation

Archaeological interpretations are based on inferences from converging material evidence of past human activities. One way to deal with mysteries in the archaeological record is to evaluate functionalities of assembled materials according to what can be known about where, how, and by whom they were used. Musical acoustics offers methodologies for these investigations, such as that of

Figure 6. *ISO-3382 room acoustics metrics (analyzed using RØDE Fuzzmeasure software) applied to impulse-response data collected at human head height in front of the central bison painting in the Marsoulas Cave as shown in* ***Figure 5****. Reverberation time (T30) is shown, with good agreement across the four channels of the first-order Ambisonics (FOA) microphone (Zoom H3VR) that recorded the impulse responses that were generated via exponential sinusoidal sweeps through a portable omnidirectional loudspeaker (Bose Soundlink Revolve+). Values from the four cardioid outputs of the FOA microphone are plotted (****colored lines****) along with their average values (****black line****).*



the small perforation through the spire of the Marsoulas conch (**Figure 3**). From a functional point of view, a hole of this size was not required to make the conch sound. If somewhat larger, the aligned holes through two internal turns would be expected to disrupt sound propagation and reflections within the conical bore (Wolfe, 2020; Campbell et al., 2021). However, because of their small diameter, these two internal holes neither improve nor prevent the horn's sounding. Although such a small perforation would not enable the attachment of an external mouthpiece, tests demonstrated that a small bone, like the bones from birds that have been used to produce some Paleolithic flutes (Atema, 2014), can be fit through the Marsoulas conch's open spire and the two aligned holes. Whereas a small-diameter tube is not optimized as a mouthpiece extension, one hypothesis is that the interconnection of a bone flute with a conch shell horn would constitute an amalgamation of sound-producing instruments used during the Upper Paleolithic, a feature that could be seen as evidence for human experimentation in joining together different musical tools. Analogous to a visual expressive culture that appears to mix features of species in some cave paintings, musical instruments created from parts of different animals could be likewise formally combined. This anthropological hypothesis about craft production is supported by the musical acoustics research that shows that the bone-conch amalgamation, although not optimal for sounding, does not prevent the conch from being used as a lip-valve instrument/natural horn.

Archaeology and acoustics can be interrelated to explore the visual-expressive connection between the Marsoulas conch and the cave from which it was excavated. It is notable that the curved interior of the shell's lip and the walls of the cave where the shell was recovered were treated with a similar pigment application technique (Fritz et al., 2021). The similar painting of the shell's interior and its cave's interior suggests a deliberate human linkage of multisensory materials. Acoustical science can be used to explore the physical interaction potentials of the shell horn in relationship to the cave from which it was excavated and to evaluate and demonstrate multimodal interrelationships. The preliminary acoustical study of the Marsoulas Cave provided an initial documentation of its spatial acoustics as well as insights regarding sonic features at the location of its central bison panel, whose red-dot painting technique parallels the markings inside the lip of the Marsoulas conch. Acoustics, archaeometrics, and anthropology together inform a developing archaeological narrative about a place where music and visual art seem to have been made together 18,000 years ago. Further research will enable interpretations that can be experientially demonstrated by virtually joining visual art and music reconstructions in spatial context.

Musical Directions for Rock-Art Acoustics

Acoustical explorations between musical instruments and the proposed locations of their sounding offer exciting possibilities for new archaeological investigations, as detailed in this overview of the Marsoulas conch and cave study. By documenting the acoustical features of the associated conch and cave, this study takes an approach distinct from precedents in rock-art acoustics, including studies of open-air sites and caves, that can be summarized according to a dominant premise. Following the initiation of research on sound in decorated caves that employed human vocalizations to evaluate resonance effects (Reznikoff and Dauvois, 1988), acoustical measurements in rock-art sites have been conducted to search for patterns of similar acoustical features across locations of artworks (Fazenda et al., 2017). More recent research has sought to relate the acoustics of a painted cave facsimile to the acoustics of an actual cave, the well-known Lascaux Cave, with similar attention to noted sound effects (see archeologie.culture.fr/lascaux/en).

> "Early visitors of the original Lascaux cave were impressed by some unusual acoustical effects. They observed the relative silence in the cave, which led everyone to instinctively reduce voice levels while entering. Then the soundscape gives the impression that some animals are shouting, running, talking..." (Commins et al., 2020, p. 919).

Similarly, leading research in rock-art acoustics continues to focus on the documentation of human-observed sound effects in acoustical and auditory perceptual terms to connect spaces with human experience (Mattioli and Diaz-Andreu, 2017). The study of rock-art site acoustics has been positioned as a problem for methodological development (Diaz-Andreu and Mattioli, 2017), and the Marsoulas study calls attention to a new research domain for both open-air and enclosed rock-art sites, considering the interrelationships of distinct modes of expressive cultural production without an emphasis on particular sound effects and instead proposing multimodal explorations of acoustical context and interaction features. Music archaeology, despite its ephemeral topic, can be studied by relating sound-producing instruments to plausible sites of their use that are better known for visual-expressive culture.

Exploring the mechanics of archaeological materials, objects, and structures was once only a possibility through direct testing and experimental reconstructions of instruments using archaeologically substantiated materials and techniques. Now, in addition to physical experimental methods, computational acoustical models enable virtual testing and reconstructions beyond the creation of three-dimensional (3D)-printed replicas that can be produced for aerophones in particular (Katz, 2016). Acoustical measurements of sound-producing instruments and associated spaces provide data to drive computational models and verify these archaeological reconstructions, with direct applications in auralization simulations. Acoustics research opportunities abound in both fieldwork and virtual domains!

Music Archaeology into the Future

Although musical content cannot be recovered from most material remnants of past life, except in the case of materials with musical notation and, more recently, audio recordings, new approaches to music archaeology leverage physics. How instruments work and how their acoustics interact with performance settings can be tested experimentally (Kolar, 2020), related to performance-setting acoustics (Boren, 2021), and, for landscape contexts, estimated using geographical information system (GIS) tools (Witt and Primeau, 2019). These reconstructive explorations can be shared with public audiences via both data visualizations and auralizations, combining cultural heritage spatial acoustics (Katz et al., 2020) with anthropological treatments of sonic communication in the form of music. Cross-disciplinary collaborations unite the distinct areas of expertise required in relating materials and mechanics to human expressive culture. For example, the pioneering European Music Archaeology Project (see emaproject.eu) produced novel explorations of archaeological sites, including caves (Till, 2014), with a musical focus, featuring creative reconstructions of music performed in archaeological acoustical simulations.

The Marsoulas conch and its Magdalenian resting place in the Marsoulas Cave in southern France offer unprecedented physical evidence of the interconnectedness of visual art making and music. Acoustical science has enabled a functional evaluation of this proposed ancient musical instrument and provided empirical means for characterizing the sounding relationship of the shell horn with a likely context for its performance, despite 18,000 years of silence. Around the world, recent integrations of acoustics and auditory science research in music archaeology are revealing new evidence about sonic expressive culture throughout time. Acoustical methodologies hone the re-sounding of materials and places of importance in past societies, enabling physics-based explorations of music archaeology for audiences today.

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