Archaeoacoustics: Re-Sounding Material Culture

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Archaeoacoustics probes the dynamical potential of archaeological materials, producing nuanced understandings of sonic communication, and re-sounding silenced places and objects.

Acoustical Experiments in Archaeological Settings

Acoustical First Principles in Practice: Echoes and Transmission Range

Atop a 150-meter-long, 3,000-year-old stone-and-earthen-mortar building, 20 to 40 meters higher than surrounding plazas, two Andean colleagues and I listened to cascading echoes produced via giant conch shell horns known in the Andes as *pututus* (see **Figure 1**). Riemann Ramírez, José Cruzado, and I were testing and documenting the performance of an archaeologically appropriate sound source at the UNESCO World Heritage site at Chavín de Huántar, Perú (available at acousticstoday.org/chavin), located at the center of a 400- to 500-meter-wide valley 3,180 meters above sea level. Our objective for this experiment, conducted in 2011, was to measure sound transmission via its return from landform features surrounding the site. Although we concurred that we perceived the echoes "swirling around from all directions," our mission that day was more than reporting subjective impressions. By recording the initial sound and returning echo sequence using a co-located audio recorder, along with the ambient conditions of temperature and humidity important to calculating the contextual speed of sound in air, I could make precise calculations in postsurvey data analyses regarding the distances of surfaces producing discrete echoes. Via this typical archaeoacoustical experiment, we confirmed that the closest rockface on the steep western hillside, known to locals as "Shallapa," produced discrete audible echoes with little signal distortion. The test also demonstrated that transmission of the sound of large *Strombus* pututus, which measure around 96 dB(A) at 1 meter, was effective to at least 1 kilometer away from the site because strong echoes returned 6 seconds later (Kolar et al., 2012, pp. 45-46). This range is consistent with undistorted and audible pututu sound transmission between the site and several archaeologically relevant landform features of the surrounding valley. Pututus such as these were excavated from the 1st millennium BCE architecture at Chavín and continue to be important throughout the Andes today. Therefore, our study not only provided dynamical specifics regarding pututus in the Chavín context but also measures extensible to the archaeology of societies such as the Inca empire that dominated South America 2,000 years later.

Archaeoacoustics: An Archaeological Science

Archaeoacoustics is a developing field that offers the acoustical community an opportunity to work across disciplines to explore the significance of sound throughout time and across cultures. Archaeoacoustical discoveries often begin with the documentation and mechanical explanation of sound effects or the experimental testing of what can be heard from where. However, *archaeology* is about putting such findings in human context.

Archaeology spans human time and is about understanding human experience through indirect evidence rather than direct accounts. From excavations of ar-

Figure 1. *Ancient sound-producing instruments. Shown are 2 examples of 3,000-year-old marine conch shell horns known as "pututus" excavated in 2001 as a cache of 20 at the Andean Formative ceremonial center at Chavín de Huántar, Perú. Photographs courtesy of José L. Cruzado Coronel (**left**) and John W. Rick (**right**). Programa de Investigación Arqueológica y Conservación Chavín de Huántar.*

chitectural ruins to examinations of recently abandoned places or discarded objects, archaeological discoveries stem from what archaeologists call *material culture*. An interdisciplinary and anthropological social science, archaeology reaches across fields to harness tools and expertise (Trigger, 2006). More than an application of acoustics to archaeology, archaeoacoustics mobilizes science, engineering, and humanities research to produce archaeological interpretation. Through methods including experimental tests, analytical models, and computational reconstructions, archaeoacousticians explore and demonstrate the dynamical potential and sensory implications of archaeological materials.

There are numerous and diverse examples of excellent archaeoacoustics research (e.g., see case study discussions in Scarre and Lawson, 2006), best recounted by the researchers themselves. Here, I offer an overview of experimental approaches to archaeoacoustics via firsthand accounts, including an interview with archaeoacoustics pioneer and Fellow of the Acoustical Society of America (ASA) David Lubman. An acoustical consultant, Lubman was awarded the Helmholtz-Rayleigh Interdisciplinary Silver Medal in Architectural Acoustics and Noise by the ASA in 2004 for work in noise and standards and for contributions to architectural and archeological acoustics (e.g., Lubman and Wetherill, 1985).

Archaeoacoustics in Practice: Multidisciplinary Research

An Interview with David Lubman

A common starting point in archaeoacoustics fieldwork has been the evaluation of location-based sound effects, especially in relation to historical accounts, mythological premises, and public and ceremonial architecture. Lubman (2016) has explored sound effects at the Maya site Chichén Itzá, México, since 1998. Lubman's approach to archaeoacoustics is exemplary in its melding of humanities perspectives, social science, and experimental and analytical acoustical methods. In his work, nonacoustical background research provides context for acoustical investigations. The importance of archaeological context to archaeoacoustical research should not be understated. Among the many secondary accounts of Lubman's research, some writers have devalued the anthropological information that Lubman considers in both research design and interpretation. Dismissal of nonacoustical forms of data that are culturally pertinent to an archaeoacoustical investigation demonstrates a basic misunderstanding of archaeology. Archaeologists interpret materials in cultural contexts and physical settings to create narratives about plausible aspects of past human life from the "things" and places that were important to individuals, groups, and societies (Wiley, 2002).

Lubman works independently of archaeological projects to explore the acoustics of places of persistent human interest. Lubman's method brings together knowledge from history, literature, and auditory science, yet the driving impetus is his multifaceted acoustical engineering expertise. In 2007, Lubman presented one such cross-disciplinary exploration, "The Acoustician's Tale: Acoustics at the Shrine of St. Werburgh" to the 42nd International Congress on Medieval Studies. In this research, Lubman looked to European literature and history to understand religious pilgrimages to shrine sites where saints would be *petitioned* (prayed to) through contact with their relics, such as the basis for Chaucer's 1387 *Canterbury Tales*. Such accounts serve in archaeology as *anthropological analogies* rather than as contextual

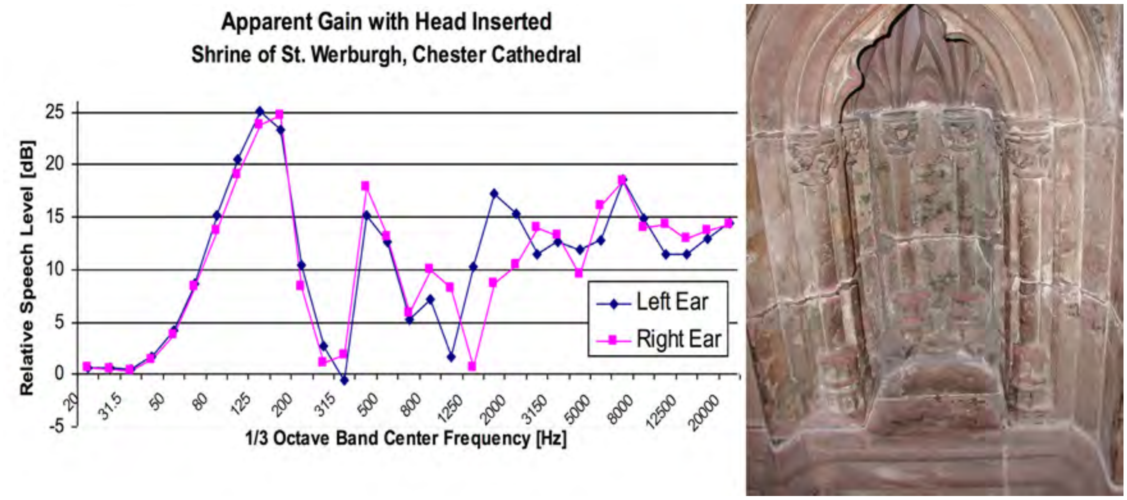

Figure 2. *David Lubman recorded binaural speech and calculated the apparent gain (**left**) produced by introducing one's head (as if to recite prayers) into the recesses of the St. Werburgh Shrine (**right**) at Chester Cathedral in 2003. Figure courtesy of David Lubman.*

evidence. Lubman recounts the study (Personal Communication, 2018):

"The unusual sound at the shrine of St. Werburgh, at Chester Cathedral (see chestercathedral.com) in western England, was brought to my attention in 2000 by the English architect Peter Howell and the architectural historian Julia Ionides of the Dog Rose Trust, a registered English charity. Peter and I visited the Shrine at Chester in July 2003. The shrine had been constructed, moved, rebuilt, damaged, and repaired, with these architectural changes traceable historically. I conducted an acoustical experiment to test functional questions about the role of sound in the *petitioning process*, the prayer requests a shrine visitor makes to the religious figure(s) represented in the shrine. The shrine is constructed with six recesses that can receive the head of a kneeling petitioner. In pre-Reformation times, prayers were spoken while petitioners knelt at the shrine with their heads in its recesses (**Figure 2, *right***). What did a petitioner hear? Did the shrine's acoustical architecture enhance the petitioner's experience? My acoustical experiment at the shrine sought to find the difference in speech quality and spectrum levels heard with one's head in the shrine versus one's head outside the shrine. I used head-worn binaural microphones to create a high-quality digital recording made with the talker's (my own) head first inside (see **Multimedia File 1** at acousticstoday.org/lubman-multimedia) and then outside the shrine recess (see **Multimedia File 2** at acousticstoday.org/lubman-multimedia), with the same vocal effort maintained in both recordings. I then produced a graph of the apparent gain with the head inside the shrine (**Figure 2, *left***), across third-octave bands in the hearing range, comparing the signal from both ears, that tracks how speech levels are greatly enhanced over the range of human hearing when one's head is located inside a shrine recess. From an interpretative perspective, recess acoustics elevate the petitioning event to "theater!" Within the shrine recesses, petitioners would hear their own voices reinforced, and they would thus be prompted to reduce voice level (in psychoacoustics, this is known as the *Lombard effect*). Inside the recesses, petitioners would be less aware of other sounds in the cathedral. The petitioners' voices are reverberated, creating a mysterious-sounding "reverberant halo," an effect that might seem like talking to another world. In this physical and religious context, the auditory percept of *proximity* may be interpreted as spiritual intimacy. My reconstructive experiment in re-creating petitioners' aural experience is a way of re-creating history, demonstrating how sensory experience is another way of knowing."

Lubman's study of the Shrine of St. Werburgh provides an empirical complement to historical archaeology, which draws heavily on written texts for experiential accounts. Lubman's experimental reconstruction produced a recorded demonstration, backed by acoustical metrics, for the architectural transformation of speech within the shrine recesses. Via archaeoacoustics, the effects that were once only possible to experience in person, in situ, can be demonstrated off-site via Lubman's audio recordings (see links above).The quantitative data from the archaeoacoustical experiment detail the amount of vocal enhancement specific to the experimenter, yet analysis of its frequency dependency enables the estimation of the shrine's acoustical effects for other talkers, thus making the research extensible to archaeological estimations. Archaeoacoustical scenarios that could be modeled using Lubman's data include charting the difference in acoustical feedback for people with different vocal ranges and characterizing a range of potential experiences. Lubman's documentation and acoustical analysis of the sonic enhancement effect of medieval European shrine architecture demonstrates a physical basis for the spiritually transformative experience recounted in historical documents and elaborated in literature.

Sound as Archaeological Evidence: Archaeoacoustical Theory and Method

Disciplinary Background: Studying Sound in Archaeology

Because archaeology employs experts from many fields, the exploration of sound-related archaeological concerns by acousticians might seem a typical collaboration. However, acoustical science is a novel and infrequent addition to the archaeological toolkit, with sonic concerns typically given cursory mention if not ignored. Until recently (e.g., Scarre and Lawson, 2006), sound as a topic for archaeological inquiry was assumed common sense or relegated to musicologists, who primarily deal with nonsonic musical culture, such as textual and graphical representations of musical practices or the reconstruction of instruments and tuning systems. The habitual dismissal of sound as a topic for archaeological study may relate to the mismatch between ephemeral understandings of sound and the premise of contemporary archaeology. Archaeologists investigate human experience *indirectly*, inferring human actions on things and places from material evidence (such as "use-wear" marks on objects) rather than from direct accounts by individuals. Despite its material basis, archaeology often incorporates knowledge from the ethnographic work of anthropology or *ethnomusicology*, where testimonials and practices are recorded from living humans, or from the *narratives* that constitute written history, to form *analogical* or *corroborative* arguments. In practice, archaeological interpretation is a nuanced process of identifying and interrelating converging forms of evidence of human actions and related environmental factors.

Sensory Phenomena in Archaeology

Both archaeology and acoustics focus on materials. The inferential logic that transforms sound into archaeological material requires a discussion of mechanics and relationships. Such conceptualization is not unlike the logic that archaeologists use to trace the effects of human actions and environmental processes on cultural materials. However, studying sound and humans requires an examination of sensory, perceptual, and cognitive aspects of sonic experience. Human-produced and received sounds have physiological and psychological ramifications, studied via psychology in the direct study of living humans. In contrast, archaeology is about the indirect study of human life via materials. Although in recent decades, archaeology has taken an experiential turn (e.g., Shanks, 1992; Hamilakis, 2013), with growing discourse around sensory concerns (Day, 2013) and even incorporating cognitive neuroscience (Renfrew et al., 2009), such literature typically discusses sound from a philosophical rather than a scientific perspective.

Archaeoacousticians directly address the sensory implications of material archaeology and, although often reference psychoacoustical quantities, infrequently apply auditory scientific methodologies in detailed studies of archaeological sites or materials. My dissertation research leveraged experimental psychoacoustics to evaluate experiential implications of Chavín's interior acoustics, situating systematic auditory localization experiments within the archaeological architecture (Kolar, 2013). In these experiments, the sound stimulus was a recording of a site-excavated conch shell horn (a Chavín pututu), chosen for both its ecological validity to the archaeological context and its sonic characteristics of a noisy attack and tonal sustain. To facilitate a consistent stimulus across all combinations of source and listener locations, the pututu sound stimulus was recorded with a microphone located at the instrument bell and reproduced in the experiment through matching single-driver, directional loudspeakers (Meyer MM-4XP) calibrated to 96 dB(A) at 1 meter to approximate the sound level and directionality of these conch shell horns. **Figure 3** is an architectural illustration from survey data of one of the two Chavín galleries where the experiment took place, with a scaled 1.68-meter human figure depicting eight sequentially tested participant positions with facing directions (labeled "POS") and six separately sounding stimulus locations (labeled "SOURCE") where loudspeakers were directed away from nearest walls. The experiment produced data towards understanding how the waveguide-like architecture influences localization cues in this purported ritual environment (Kolar, 2013), research that initiated what I refer to as "sensory-spatial mapping" of the archaeological setting.

Reconstructing and Interpreting Archaeological Sound

Although this article features experimental archaeoacoustics research that explores extant architecture, instruments, and sites, some archaeoacoustics work is more theoretical, based on reconstructions using computational modeling techniques and dynamical estimations. For experimental observation, whether in situ or in models, sound must be generated via some form of vibratory excitation or a mod-

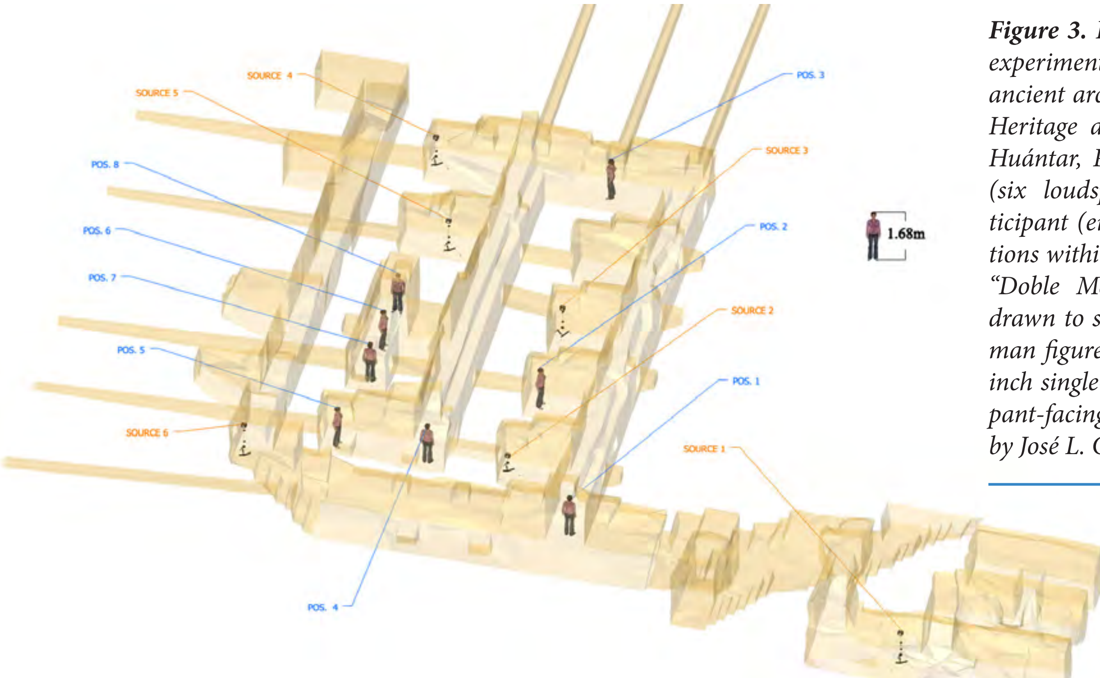

Figure 3. *Diagram of auditory localization experiment conducted in situ within the ancient architecture at the UNESCO World Heritage archaeological site at Chavín de Huántar, Perú. Shown are sound stimulus (six loudspeakers; "SOURCE") and participant (eight human figures; "POS") locations within the interior space known as the "Doble Ménsula (double-corbel) Gallery," drawn to scale as shown by 1.68-meter human figures. Directionality of calibrated 4–inch single-driver loudspeakers and participant-facing directions as drawn. Illustration by José L. Cruzado Coronel (Kolar, 2013).*

eled sound source. If archaeological sound must be reconstructed to be observed, is archaeoacoustics, therefore, a purely interpretative practice? Reconstruction and interpretation, although related, are not the same. The interpretative aspects of archaeoacoustical reconstruction depend on the way in which sound is produced as well as the choices of source and receiver locations that reenact human perspectives for contextual sound transmission.

Archaeoacoustical measurements made by exciting spatial or instrumental acoustics using an impulse (approximating a Dirac function) or a robust method for generating a spatial impulse response, such as the repeated exponential sinusoidal sweep technique developed and refined by Farina (2007), reveal archaeological acoustical features rather than reconstruct specific sounds. The impulse response can be thought of as a "spatial identifier," a composite acoustical feature set that reveals how the physical constituents of a space or instrument affect sound propagation. In contrast, human-performed acoustical test sounds, via artifact or replica instruments, are more interpretative, although the choice of particular instruments and the ways of playing them can be aligned with archaeological evidence. Reconstructive modeling and auralization of spatial and architectural acoustics likewise involve choosing sound sources and many other interpretative factors related to content, sound-making physics, and listener perspectives. Reconstructive interpretation, when informed by archaeological evidence, emphasizes the plausible rather than speculative.

Archaeoacoustical Interpretation in Archaeological Research

Archaeoacoustics produces assessments of the dynamical potential of archaeological materials, to support broader archaeological interpretation. The fieldwork and conservation program led by John Rick at the 3,000-year-old UNESCO World Heritage site at Chavín de Huántar, Perú, has invited and included archaeoacoustical collaboration since our project was formed at Stanford University in 2007. **Figure 4** shows several archaeoacoustical techniques employed in research at this well-preserved ceremonial complex that occupies about 14 hectares. In this research, converging forms of material cultural evidence support understandings of ancient communication (Kolar, 2017), including data from acoustical measurements of both site-excavated conch shell horns (Cook et al., 2010) and the well-preserved stone-and-earthen-mortar architecture. At Chavín, the only sound-producing instruments, either represented graphically (see **Figure 5**) or site excavated (see **Figure 1**), are the "Chavín *pututus*," marine shell horns made from the eastern Pacific giant conch *Strombus Lobatus galeatus*. Because no written texts are known from Chavín, we can only infer from material evidence, including extensive use-wear to the shells, that these instruments were performed at the site.

Pututus may have been performed in many places in and around the Chavín ceremonial complex during the 1st century BCE. Their performance physics in groups produces compelling effects for Chavín's ritual context, especially

***Figure 4.** Since 2008, the author has adapted a variety of acoustical measurement techniques in fieldwork at archaeological sites including Chavín de Huántar, Perú (ccrma.stanford.edu/groups/chavin), using both loudspeaker-reproduced and human-performed sound sources, captured via multiple-microphone arrays and in-ear microphones. Photograph by José L. Cruzado Coronel.*

within the confines of interior architecture (Kolar, 2014; acousticstoday.org/pututus). However, converging forms of archeological evidence points to the performance of of pututus in and around the site's Circular Plaza. Alongside this 21-meter-diameter, semienclosed, countersunk plaza, the Chavín pututus were excavated in 2001 as a group, deposited along the walls of a small room. The plaza's decorated, relief-carved interior walls feature two known depictions of pututu performers (**Figure 5**), and several floor paving stones include fossil sea snails, the instruments' ancient ancestors. In 2009, acoustical impulse-response measurements were conducted in and around the partially intact Circular Plaza, within the Lanzón Gallery, the interior space to which it acoustically couples by way of three ducts. Repeated experiments using a precision loudspeaker and a spaced array of omnidirectional microphones through these ducts revealed that they are near-perfect filters for frequencies in the sounding-tone range of the Chavín pututus. The center duct between the interior gallery and exterior plaza, which is visibly aligned with the carved mouth of the *Lanzón*, a granite monolith historically reputed to be an "oracle" (**Figure 6**), further privileges pututu acoustics by emphasizing frequencies around 900 Hz (in the range of the instruments' third harmonic) that is an important timbral signifier (see **Figure 7**; Kolar et al., 2012).

Whether or not one concurs with the archaeological interpretation that suggests pututu performers could enact a metaphorical "line of speech" by sounding the instruments

***Figure 5.** Relief-carved stone plaques lining the 21-meter-diameter Circular Plaza at Chavín de Huántar, Perú, depict figures holding conch shell horns (pututus) as if in performance. Photographs by José L. Cruzado Coronel and Miriam Kolar.*

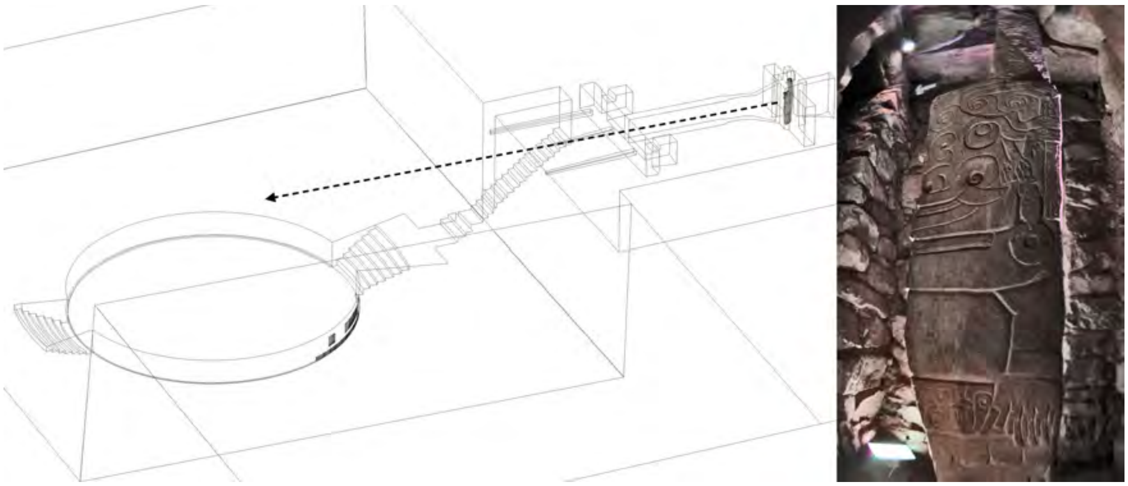

*Figure 6. Architectural reconstruction of Chavín's Lanzón Gallery and Circular Plaza (**left**) and the 4.5-meter granite monolith known as "the Lanzón" (**right**). Illustration and photograph by José L. Cruzado Coronel.*

between the Lanzón monolith and the Circular Plaza (see **Figure 6**; Kolar et al., 2012), repeated measurements have demonstrated that these ducts acoustically favor pututu sound and perceptibly filter out higher frequencies crucial to speech clarity, for example. Pututus would have been useful in transmitting sonic information between the access-restricted Lanzón Gallery, where the Lanzón "oracle" monolith (**Figure 6, *right***) is located, and the larger public gathering area outside, the Circular Plaza (**Figure 6, *left***). Whether or not the pututus would have been considered the voice of the oracle is an interpretative matter. From a physical dynamical perspective, we can assert that pututu sound transmission is facilitated architecturally between these spaces. In this research example, archaeoacoustics strengthens material archaeological associations by demonstrating dynamical context for the Chavín pututus within the ceremonial locus of Chavín's Circular Plaza. Architectural acoustical evidence, data from my team's acoustical study of the site-excavated pututus (Cook et al., 2010), and other archaeological information together support archaeological arguments for location-specific pututu performance at Chavín.

Archaeoacoustics and Music Archaeology

Likely due to the custom of identifying sound-producing instruments with music and an established scholarly path for musicological studies, the field of music archaeology precedes archaeoacoustics. Despite substantial attention to the acoustics of well-preserved amphitheaters, an area of archaeoacoustics dominated by architectural acoustical modeling research, European classical archaeology has emphasized musical concerns identified from texts and visual representations. Archaeological materials readily identified as "musical" are typically studied by music archaeologists, who employ musicological tools and methods concerned with the abstract, conceptual, structural, and performed aspects of music (its "culture") rather than sound (its "physics"), which has historically been the domain of musical acoustics. However, in archaeological practice, such culture-communication dichotomies are dissolving, and much as historical musicologists increasingly consider the acoustics of instruments and performance spaces, music archaeologists have begun to incorporate acoustical concerns.

Two recent studies led by scholars of art and architecture offer notable incorporations of archaeological acoustics, the Renaissance religious architectural study of Howard and Moretti (2009) and the multisensory exploration of Hagia Sophia in Byzantium by art historian Bissera Pentcheva (2010, pp. 45-56; demonstrated in this video available at acousticstoday.org/hagiasophia). Howard and Moretti's (2009) study included the reconstruction of musical performance practice in a dozen churches of Renaissance Venice, accompanied by audience surveys regarding perception of architectural acoustical attributes that were measured and modeled. Pentcheva's (2010) research considered the metaphorical value of sound in combination with light, human movement, and other elements of early Christian ritual in Constantinople. Historical musicologists and the choir Capella Romana worked with Pentcheva and Stanford musical acoustics colleagues to reconstruct period music as if performed within the 11-second reverberant setting of Hagia Sophia (heard on the video above).

For archaeological contexts including sound-producing instruments, it is difficult to avoid experimental and experiential engagements of archaeological materials. Making sound in places seems to have been a conscious human activity throughout time, as, for example, Morley (2003), Blake and Cross (2015), and Tomlinson (2015) among others have de-

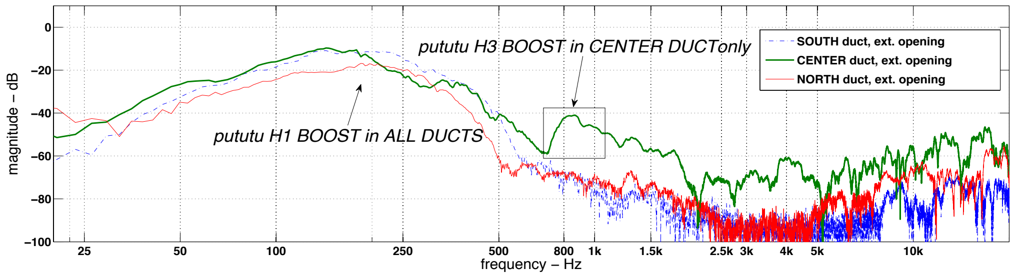

Figure 7. *Magnitude frequency measured at the exterior openings of the three ducts connecting Chavín's Lanzón Gallery with its Circular Plaza via the repeated sinusoidal-sweep impulse-response method. The sounding-tone range (H1) and articulation peak (H3) of site-excavated conch shell horns (pututus) are privileged by duct acoustics. Adapted from a diagram by Miriam Kolar and Jonathan S. Abel (Kolar et al., 2012, Figure 13).*

tailed. Indeed, sonic engagements with archaeological sites, whether or not musicological in purpose, have frequently stemmed from reconstructive soundings (often hand claps, footsteps, or whistles) as, for example, archaeoacoustics pioneers Paul Devereux (2001), Iegor Reznikoff (2006), Wayne Van Kirk, David Lubman, and rock art specialist Steven Waller have recounted in professional venues and in the popular press, among work by others too numerous to list here. *Acoustics Today* previously featured the work of Jelle Atema (2014), Professor Emeritus of Biology, Boston University, and Adjunct Scientist, Woods Hole Oceanographic Institution, MA, a flutist who studied with renowned performer Jean-Pierre Rampal. Atema has innovated the experimental reconstruction, performance, and organological exploration of flute technology, offering a comprehensive, physics-based perspective on ancient music making.

Although cross-disciplinary expertise is a hallmark of individual archaeoacousticians, collaborations across multiple fields drive unprecedented explorations of ancient sonics, which often result in formal musical performances for audiences. In 1992, musical acoustician Murray Campbell, musicologist John Purser, archaeologist Fraser Hunter, silversmith John Creed, and musician John Kenny began a multidisciplinary archaeomusicological reconstruction of the *carnyx*, a Celtic brass instrument based on fragments excavated in northeastern Scotland (Campbell and Kenny, 2012; acousticstoday.org/carnyx). Their collaboration has produced numerous archaeological engagements, including concert presentations of the carnyx in venues such as the 2018 Experimental Music Archaeology Symposium at the State Archaeology Museum in Brandenburg, Germany. Musicians such as Swiss trombonist Michel Flury have explored archaeological contexts to develop new musical interpretations on replicas of ancient instruments, such as Flury's series of Chavín-inspired performances with modern pututus that were featured in a local concert in that Andean town, followed by music for an international exhibition by the Museum Rietberg in Zurich, Switzerland, and continuing in current work (Flury's *Klanginstallation Chavín* available at vimeo.com/245501948). Beyond performance practice, music archaeologists are increasingly incorporating acoustical concerns and methods to characterize and contextualize musical materials, especially for artifact instruments of sound production that can be played or convincingly reconstructed (Both, 2009).

Mapping the Potential for Sonic Communication

Following the premise of sound as a near-universal means for human communication, archaeoacoustics is frequently concerned with establishing the plausibility of what can be heard and from where, dependent not only on acoustical science but also information from site archaeology. Archaeological context includes considerations about who would be hearing what sonic material, under what environmental conditions, and in what social or political settings. Archaeoacoustical studies frequently seek to test interpretative or historical claims as well as provide experimental evidence for sonic dynamics not reported or considered by others. For comparison and contrast with my initial discussion of the Chavín pututu echo study and to show how archaeoacoustical tools and methods can be adapted across archaeological contexts, I offer an example of an outdoor archaeoacoustical survey that also employed a *Strombus* pututu as one of several sound sources. To produce empirical data on site-specific sound transmission as well as test claims from many archaeological and historical accounts regarding the role of sound and architecture in Inca governance, archaeologist

Figure 8. *Acoustical survey on and around the central platform ("ushnu") at Inca Huánuco Pampa, Perú. Photograph courtesy of Miriam A. Kolar.*

R. Alan Covey, Andean experimentalist José Cruzado, and I designed and conducted an acoustical survey at the large Inca administrative city Huánuco Pampa. This imperial complex, active in the early 16th century, occupies a remote, high-Andean *pampa* (plain) 3,800 meters above sea level. Site architecture is organized around a plaza measuring 550 × 350 meters (19 hectares) with a raised central platform of 32.5 × 48 meters (see **Figure 8**; Kolar et al., 2018).

Conch shell horns figure prominently among sound-producing instruments mentioned in Spanish colonial accounts of the Inca empire, where they were known as long-distance communication devices carried by *chasqui* messengers. In the acoustical study at Huánuco Pampa, we used a *Strombus* pututu as one of a sequence of archaeologically appropriate instrument types to cross-compare the effects of frequency and production mechanism across mapped survey points. To provide a standard reference, we employed an electroacoustical test signal that is preferred for architectural acoustical measurements to produce impulse responses, which we also generated manually via a handheld percussion instrument (wooden clappers). In the broad Andean plain where Huánuco Pampa is located, simultaneously surveying colleagues reported hearing our tests in distant site sectors. Extrapolating our measured sound levels over the site map demonstrated the likely audibility of pututus to its perimeters (which extends 1.7 kilometers from the central platform), consistent with other data on pututu sound transmission. Postsurvey analyses of the recorded audio suggested that the particular frequency range of large Andean pututus (centered around 300 Hz), in combination with typical ambient daytime conditions in the central Andes (low humidity and moderate temperatures), makes them practically immune to wind shear, which is one of the environmental characteristics of high-altitude Andean sites, especially in the late morning through afternoon (Kolar et al., 2018). Theory-backed acoustical experimentation thus supports cultural evidence linking these instruments to political power in the Andes from the present back to the Inca (approximately 13th to 16th centuries CE) and as early as Chavín (1st millennium BCE).

Archaeoacoustics: Acoustical Science in the Service of Archaeology

Working at a new scientific frontier, archaeoacousticians responsively adapt acoustical science methods to archaeological research. An archaeological science, archaeoacoustics enables specific characterization of sound-related matters and methods for evaluating the extensibility of findings from one context to others or generalizing findings to a broader archaeological interpretation. Archaeoacoustical research worldwide has demonstrated the feasibility of adapting acoustical theory and methods to diverse archaeological sites and materials. Archaeoacousticians re-sound silent traces of past life, bringing the past into the sensory presence. This unique combination of science and humanities research provides novel opportunities for thinking and working across disciplines. Archeoacoustics connects the human experience across time and geography.

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BioSketch

Miriam Kolar's cultural acoustics research leverages acoustics and psychoacoustics to study sound in cultural contexts. Since 2008, she has led archaeoacoustics research at the UNESCO World Heritage site Chavín de Huántar, Perú, where her methodological innovations include on-site auditory localization experiments to evaluate experiential implications of archaeological architectural acoustics. Recently a Weatherhead Fellow at the School for Advanced Research (SAR), Santa Fe, NM, Kolar received her PhD as a Stanford Interdisciplinary Graduate Fellow at the Center for Computer Research in Music and Acoustics (CCRMA), Stanford University, Stanford, CA. Prior to her doctoral study, Kolar engineered concert sound design and location recordings, and directed the CalArts under-graduate music technology program.