Research Article

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Employing Psychoacoustics in Sensory Archaeology: Developments at the Ancient Sanctuary of Zeus on Mount Lykaion

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Abstract: Psychoacoustics offers a promising, subject-centred approach in unlocking the sonic experience of past built spaces. Its tools and metrics offer tempting responses to an essential challenge of sensory archaeology practice: the rendition of individual experience as data. How can one person's experiences be compared with another's towards generalized observations? Moreover, what can be said about past experience as a result? These questions are central to the ongoing acoustic consideration of the ancient sanctuary of Zeus on Mount Lykaion. Here the landscape that binds the sanctuary ruins offers noteworthy moments of sonic connectivity and isolation. Building on existing scholarship based on researcher perception, a sensory approach was developed to explore the site's sonic relationships and ultimately determine what roles they could have played in original site usage, information beyond what the architecture and written record offers. Extensive site research uses first-hand sonic observation to frame a machine-based psychoacoustic analysis of binaural field recordings. Findings map out a sacred terrain of shared and singular experience orchestrated by sonic connectivity made available for further interpretation. They also underscore the necessity of caution in interpreting psychoacoustic findings themselves as an empathetic understanding of past people.

Keywords: empathy, Greek sanctuaries, Mount Lykaion, psychoacoustics, sensory archaeology, soundscape

1 Introduction

What can we learn about a site's distant past by listening to its current form? And how might we structure this analytical listening? In recent years, archaeological attentions have turned towards wider experiential modes of investigation through individual and combined senses, including through sound. Many new methods in sensory archaeology are being developed to investigate the layer archaeologists have not always prioritized: the experiential, the intangible, and the immaterial, which is nonetheless derived from the material surroundings (see for instance the variety of approaches in Brück, 2005; Fahlander & Kjellström, 2010; Hamilakis, 2015; Hamilton et al., 2006; Landeschi & Betts, 2023; Skeates & Day, 2019). A sense-based investigation can take on many forms, examining a single sense in isolation or in a synesthetic combination.

Switching the primary lens of historic investigation from visual to sonic has proven to be a rich repositioning for research (Aletta & Kang, 2020; Butler & Nooter, 2019; Fırat, 2021; Scarre & Lawson, 2006). In one

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dimension, doing so shifts attention away from what physical evidence is left towards what (form, individual, activity) is absent. But more expansively, "viewing" through listening has enabled the re-examination of interpretive assumptions, floating quotidian (though no less ritualized) experience alongside formalized, authorized constructions and narratives, and requiring new questions to be posed of existing material remains. This proves essential for sites such as the Mount Lykaion sanctuary, where the surviving architecture only indicates general programming for large (and infrequent) gatherings, despite the site very likely being used frequently for individual, daily ritual purposes outside of grand events.

In general, one can understand the sonic setting of a place as formed by two composite layers: the physical structure or environment that hosts certain acoustic effects, and the sounding practices and sources that initiate these effects. Ancient amphitheatres, for instance, were physical structures designed such that activity on the stage could be heard from any seat; performance practices developed that collaborated with the architecture and audience for this purpose.

Yet when researching a sonic setting, a third layer must be considered: human sound perception. Soundscape studies arose out of this consideration, originating with the work of R. Murray Shafer and Michael Southworth, who were contending with the elevating levels of industrial "noise" (unwanted or negatively interpreted sound) in 1960s in North American cities (Schafer, 1994; Southworth, 1969). Schafer codified his approach into what is now a primary reference for soundscape work, republished in 1994 as "The Soundscape: Our Sonic Environment and the Tuning of the World." His foundational work was expanded by the Five Villages project, which carefully studied what could be recognized today as historic soundscapes, and the influential independent work of his original team, including Hildegard Westerkamp and Barry Truax (Järviluoma, Kytö, Truax, & Uimonen, 2010; Truax, 2012; Westerkamp, 2002). Since these early concerns, soundscape study has blossomed in many research directions beyond the effects of noise. At its core, soundscape study today involves the study of a particular sonic environment according to how humans perceive it, either through live soundwalking in the environment and immediate feedback, or through lab-based studies where sounds are played for participants to respond to in some form. Humans are always the beginning of perceptual research within soundscape, and individual context is paramount. Since 2014, international standards for soundscape terminology, investigation, and analysis have been developed and published in stages under the International Organization for Standardization Standard number 12913 (ISO, 2014, 2018, 2019). This ISO standard defines the soundscape as the "acoustic environment as perceived or experienced and/or understood by a person or people, in context" (ISO, 2014) and lays out the soundscape approach as a consideration of "people, acoustic environment and context in a combination of several differing investigative methods" including psychoacoustic techniques (ISO, 2018).

The field of psychoacoustics, which studies "the relations between the physical characteristics of sounds and the evoked sensations" in organisms, has uncovered and modelled the particularities of human hearing, such as our sensitivities to certain frequencies, sound filtering mechanisms, time-based adaptations, pattern recognition, differences corresponding to age and gender, and our fine-grained spatialization of sound origins (Fastl & Zwicker, 2007; Plack, 2010b). Each plays a role in how we process a sound wave into information that we then interpret for meaning. In sound-focused research of place, one must consider the physical properties of sound as well as how it is perceived by human ears – the two realities may differ.

The examination of sound within historic settings has driven investigations from many disciplines (social sciences, humanities, and STEM included) that employ a wide range of research methodologies. As a brief cross-section, consider previous studies (Aletta & Kang, 2020; Blake & Cross, 2015; von Fischer, 2018; Gunderlach, 2007; Katz, Murphy, & Farina 2020; Mills, 2014) – efforts centred within archaeology are expanded upon in Section 3. One of the primary challenges in any discipline is documenting and communicating sound-based data: in effect, converting information from one sense into another. For researchers who employ technologically driven approaches in their efforts, the advances in both acoustic measurements and acoustic rendering offer tools (often developed for acoustical engineering) with an unprecedented guarantee of precision. It is now possible to differentiate reverberation times of individual frequencies down to the milli- or microsecond, a level of detail beyond the capabilities of human hearing. Psychoacoustics offers a promising addition to such approaches, with "objective" insights into human hearing perception based on modern human physiology; generalizations depend particularly on the capabilities of both the vocal mechanism and the inner ear, which are understood to have developed in their current forms between 50,000 and 150,000 years ago (Lieberman, 2007; Mehrotra, Srivatav, Mehrotra, & Sharma, 2020).

However, the direct application of these tools to archaeological site investigation requires some adaptation. While the consistency of measurement that such tools offer is necessary for dependable pattern recognition and verification of results, the level of precision applied to the gathered data and their analysis must be scaled appropriately for interpretive intents, especially in settings that no longer bear their original material configurations. Moreover, the original designed intent of (psycho)acoustic analyses must be accounted for prior to use; a metric developed for rating speech clarity in a closed indoor environment may produce unreliable data in an outdoor archaeological site, for instance. To put these various complexities in a row towards productive research, this study will detail the application of psychoacoustic approaches within the ancient sanctuary of Zeus on Mount Lykaion, Greece, where striking sonic connections have been observed between building ruins and distant landscape features alike.

2 Psychoacoustics as a Threshold Between Humans and Their Environment

With its origins in the spatialized experience of sound (Ouzounian, 2020, Chapter 5; Yost, 2015), the field of psychoacoustics has found productive application in the research of contemporary settings, often conjoined with soundscape studies of corresponding sonic environments (Aletta, Kang, & Axelsson, 2016; Engel, Fiebig, Pfaffenbach, & Fels, 2018; Lenzi, Sádaba, & Lindborg 2018; Genuit & Fiebig, 2017; Lenzi, Sádaba, & Lindborg, 2021; COST, 2013). As mentioned, psychoacoustic study focuses on the first reception and processing of a sound (e.g. if the sound is received as loud or part of a sound pattern) rather than either the physics of sound moving in a space or the cultural and meaning-centred responses to sound that fields such as ethnomusicology and soundscape studies address. In this way, the field of psychoacoustics studies the narrow middle-ground of human subjectivity between a sound and its eventual interpretation (Plack, 2010a).[1]

Within the field of psychoacoustics, values for frequency sensitivities, filtering mechanisms, and singularities present in the human ear–brain connection have been derived from physiological averages determined through experimental testing and subsequent modelling. “Average” hearing responses according to these characteristics have been identified, which establish general psychoacoustic metrics in standard conditions such as perceived loudness, sharpness, and roughness, pitch, and fluctuation (Fastl & Zwicker, 2007; ISO, 2017; Moore, 2014). The derived values have so far been taken to be representative across cultures and time periods, as they are applied across the vast majority of psychoacoustics research studies without baseline challenges.

Psychoacoustic analyses are conducted on sound recordings with high playback fidelity (i.e., recordings that closely resemble original conditions for the human ear) – binaural recordings are typically made, which record the spatialization of the recorded sound in addition to many attributes. This is particularly relevant for archaeological applications: such recordings may be considered closer to an archival-quality recording for future reference (much like a high-resolution photograph); additionally, the files may be revisited by future researchers for additional study and/or for verification of original conditions and conclusions. The recordings themselves are thus objects of study that can be analysed according to first-hand impressions through playback (and it must be stated that this playback is always dependent on the capacity of the machine as much as the human listener) as well as being analysed by predicted human perceptive attributes through psychoacoustic analysis. Different current archaeological schools of thought may read implicit objectivity and subjectivity of these data differently.

By using psychoacoustic methods (which are detailed in Section 4.3 for this study), a sonic condition or event is documented according to average human perception – these average values form the baseline of comparison

1 This middle-ground between objectivity and subjectivity provides an ideological tension for current archaeological practices negotiating between post-enlightenment notions of objective research truths, post-processual and sensory-based understandings of the researcher-as-interpreter, and post-humanist reassessment of objects’ agency through concepts such as vital materialism.

between recorded phenomena. For instance, adults have a consistent average assessment of the perceived loudness of a sound as well as the perceived threshold that differentiates two sounds (largely dependent on frequency; see Fastl & Zwicker, 2007, pp. 209–210). Such average values have been determined by studying many individuals in varying sound conditions and physical settings and using averaging procedures as appropriate to determine a predicted response in a listener (Fastl & Zwicker, 2007; ISO, 2017). These findings are built into the construction of digital analyses that are employed in this study and detailed in Section 4.3.

Fundamentally, psychoacoustic tools enable quantitative comparison of human sonic encounters at a perceptual level – what might otherwise be considered transitory experience (e.g. how loud a sound is perceived to be) is translated into quantifiable data. Combined with first-hand personal experience, this information can then be applied to questions of the past to infer what activities or relationships could have been facilitated by the sounded layer of the built environment. For instance, if individuals stand today in two ancient structures and cannot see each other, yet they can hear each other speak or even move, new questions can be asked about how the people and activities in these structures related to each other in the past. Would past actors modify their practices to be heard either more or less by others? Was the design of these structures informed by sound transmittance between them? Psychoacoustics is particularly important when considering certain activities, as some sounds will be more distinguishable to human ears due to their frequency or repetition, for example – think of discerning children's conversations during play vs an adult male chanting. The application of psychoacoustics within the ancient mountaintop sanctuary of Zeus on Mount Lykaion provides a case study for examining the potentials and limitations of psychoacoustics in asking these kinds of questions, combining techniques used within indoor, landscape, and historical research contexts.

3 Psychoacoustics in Archaeology

To understand how psychoacoustics has started to gain relevance in archaeology as both a concept and a set of applied tools, it is necessary to set the scene for perception in archaeology more broadly. The sensory turn within the humanities also influenced archaeological practices; as mentioned, the diversity of theoretical and applied approaches to sensory experience in past built contexts has made solid in-roads into archaeology (Brück, 2005; Hamilakis, 2013; Skeates & Day, 2019; Wetherell, Smith, & Campbell 2018). Of the many approaches, two research strands are particularly relevant for Mount Lykaion and worth mentioning as theoretical benchmarks for the project: landscape phenomenology, and what is termed either sonic archaeology or archaeoacoustics. Both archaeoacoustics and landscape phenomenology rely on human perception as the primary investigatory tool (rooted in Maurice Merleau-Ponty's phenomenological theorizations; Merleau-Ponty, 2004), and both consider acoustic dynamics within landscapes in various capacities. Landscape phenomenology explores dynamics in conjunction with a landscape more fully, including the embodied meaningful or symbolic experience to a person while transiting an area as well as from static positions (Hamilton et al., 2006; Hamilton & Whitehouse, 2020; McMahon, 2013; Tilley, 2004). Much of this work depends first on human field observation, which might subsequently be supported by measurements via instruments. This is similar to the soundscape approach and its employment of psychoacoustic analysis, an important reference for research on Mount Lykaion as well (ISO, 2014; Jordan, 2020). In contrast to the landscape scale of investigation, archaeoacoustics started with a clear focus on artefacts such as musical instruments; it has since expanded to include examinations of the acoustic dynamics within natural and built structures (for just a sampling, see Đorđević, Novković, & Pantelić 2019; Scarre & Lawson, 2006; Till, 2019; Yioutsos, 2014). This work regularly employs various sound recording tools and methodologies alongside human observation (Kolar, Covey, & Cruzado Coronel 2018; Primeau & Witt, 2018). Archaeoacoustics research of past inhabited spaces commonly examines usage patterns made possible through acoustics; for example, studies have attended to the acoustics of caves and shelters to explain where paintings or use evidence is apparent (Fazenda et al., 2017; Till, 2014; Yioutsos, 2019).

Recently, psychoacoustic considerations have begun to filter into some archaeoacoustic research, advancing speculations about the impact of sound on ancient humans where other direct evidence is absent both within structures and at the landscape scale (Kolar, 2017; Valenzuela, Díaz-Andreu, & Escera, 2020). Valenzuela et al. (2020) describe some of the challenges inherent in psychoacoustic inclusion and point to off-site predictive site modelling and lab-based sound quality assessment as new methods being explored to determine possible ancient conditions. Applications in more recently built structures have also been explored (Aletta & Kang, 2020; Gerstel, Kyriakakis, Raptis, & Donahue, 2018; Suárez, Alonso, & Sendra, 2016; Tronchin & Knight, 2016). Psychoacoustic study of Mount Lykaion's sanctuary of Zeus has been carried out since 2015. Using it as a case study, Section 4 details the specific capabilities that psychoacoustics (as opposed to approaches in acoustics or soundscape) can offer to sensory archaeology.

4 Psychoacoustic Research on Mount Lykaion

Ground-survey and excavation-based investigations have been undertaken for over two decades by the Mount Lykaion Excavation and Survey Project (MLESP) (Romano & Voyatzis, 2010). Separate from this effort, sensory-based research conducted at the site since 2015 has focused not on the static physical remains themselves but rather on the human dynamics enabled by sound that may still be latent (Jordan, 2020, 2021a,b). A main reason this site was chosen for such research was due to its intriguing sonic dynamics, the intact state of the landscape in relation to architectural features, and its continued isolation from contemporary sound sources that enabled sound recordings for comparative study. The goal of the research has been to gain a greater insight into how the sanctuary was used – what the structures were designed for, and what activities could have taken place in the terrain surrounding them. The ancient architecture is greatly deteriorated and gives up limited clues; a thin, yet invaluable, first-hand account from antiquity details the appearance of the site when the buildings were already in ruins, as discussed below. But the mountainous landscape as it stands today provides an evocative communal experience where communication can be held across great distances. Interestingly, the acoustics can change dramatically within a short distance, providing sudden disruptions in the sonic patterns one may experience between landscape and architecture. Sonic connectivity can be surrounded by patches of relative isolation, the sphere of one's acoustic reach constantly changing. The sonic connective tissue of the sanctuary, whether designed or naturally occurring, feels undamaged in comparison to the architecture. It is easy to imagine that people in antiquity would have identified the same hillsides as optimal for cheering on athletes or would have similarly been surprised by how clearly someone on a distant hillside could be heard.

4.1 Mount Lykaion/Lykaion Zeus – A Brief Site History

An orientation to the study site's development in antiquity helps establish the framework for its sonic investigation. The sanctuary to Zeus was built into the southern peak of Mount Lykaion, a prominent mountaintop sanctuary in the Peloponnesian Mountains on the historic, political, and physical border between Arcadia and Messenia. At its southern peak (1,382 m) sits the remains of an ash altar, a bedrock summit covered in a thick layer of ash from the centuries of burned sacrifices conducted in the open during ancient times. Just below are two column bases and an open area identified as a temenos or sacred precinct. Excavations at the altar have revealed evidence of use extending to the Neolithic period, but the introduction of structures can be dated to the appearance of a Mycenaean shrine in the sixteenth century BCE (Romano & Voyatzis, 2014, p. 569). Approximately 200 m in elevation below the altar is a lower sanctuary used for ritual athletic games in honour of Zeus during Hellenistic practice.

The lower sanctuary today is defined by a cluster of building foundations (Figure 1) – those identified are a stoa, small building with semi-circular walls, a fountain building, an administration or banqueting building, monumental seats with statue bases, a tunnel leading to the hippodrome, and a bathing complex. These bound a visible hippodrome and adjacent stadium area – turning posts for horse races and starting blocks for foot races have been found, and the earthwork that supports the hippodrome surface still forms clear north and

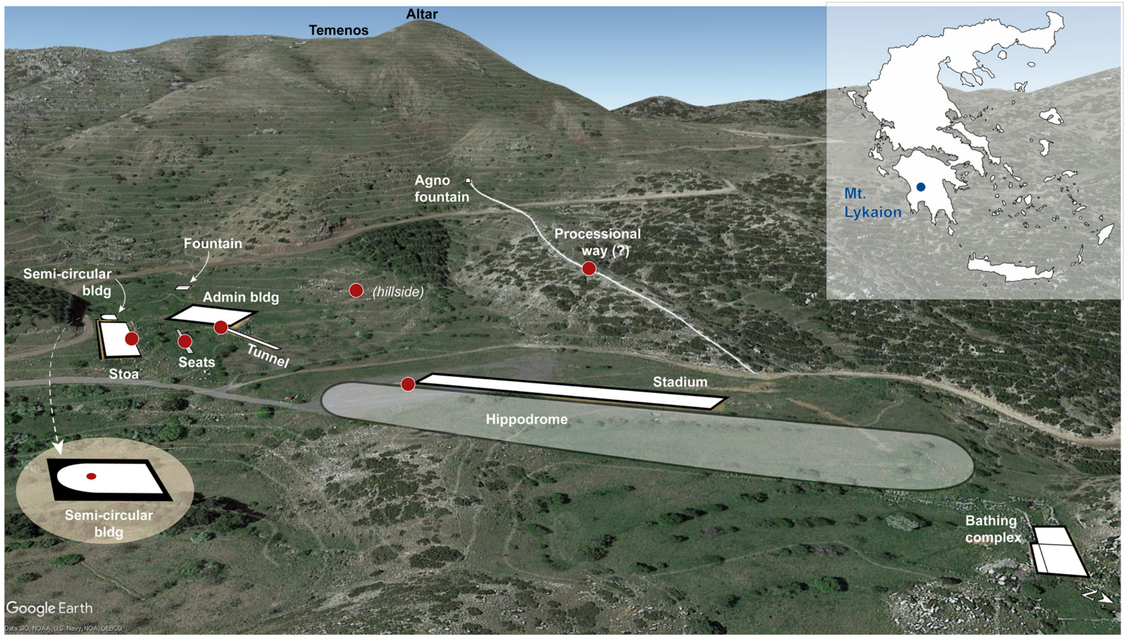

Figure 1: Bird's eye view of the Sanctuary for Zeus with built remains outlined (white text denotes lower sanctuary components); recording points mentioned in the text are shown in red; location of Mt. Lykaion in Greece is indicated in upper right corner (Image: P. Jordan).

northeastern edges. Another fountain building, known as the Agno or Hagno fountain, was constructed in a re-entrant of the mountainside approximately halfway in distance between the lower and upper sanctuaries where abundant water once flowed (Pausanias, 1918, sec. 8.38.3). It is situated at the end of what may have been a processional way along a mountain spur connecting to the hippodrome surface, and which also draws a convenient straight line between the bath and Agno fountain. All the buildings listed above were constructed of monumental local limestone blocks; the characteristic mixture of polygonal masonry mixed with rectilinear coursed layers visible in the structures supports the assertion that the buildings were constructed simultaneously in the mid-fourth century BCE (Romano, 2019; Romano & Voyatzis, 2014, 2015), perhaps coinciding with the establishment and political consolidation of the valley city of Megalopolis in 371 BCE. Such a unified and singular composition is a rarity in comparison to the more common evolution over time of other sanctuaries.

After a century and a half of usage, the Lykaion Games were relocated to the valley city of Megalopolis in 215 BCE and the lower sanctuary was apparently abandoned thereafter (Romano & Voyatzis, 2015, pp. 207–276). This indicates that the limestone structures on display today may have only been used in conjunction with ritualized athletic competitions for approximately 150 years. However, use of the site appears to have continued for at least another century for gatherings; the tunnel was transformed into a dumping site, and substantial banqueting debris dating from the second and first century BCE have been found here (Romano & Voyatzis, 2015, pp. 219–220, 269–273). A brief account of the physical environment of the lower and upper sanctuaries was made by Pausanias in the first century CE, when the lower sanctuary was already abandoned and the buildings fell into disrepair:

> There is on Mount Lycaeus a sanctuary of Pan, and a grove of trees around it, with a race-course in front of which is a running-track. Of old, they used to hold here the Lycaean games. Here there are also bases of statues, with now no statues on them. (Pausanias, 1918, 8.38.5)

The appearance of limestone architecture does not mark the dawn of the lower sanctuary, however. Evidence of earlier site activity has been uncovered under the monumental seats and hippodrome surface without the evidence of previous structures such as foundations or other support materials, indicating possible activity from the seventh century BCE (Romano, 2019, pp. 98–108; Romano & Voyatzis, 2015, pp. 207–276). This would represent 300 years of ritualized site use prior to the appearance of monumental stone architecture. It would also explain how Pindar could provide descriptions of the established "festival of Lycaean Zeus" (Pindar, 1990c) and celebrated athletic victors from the fifth century BCE, at least 100 years before the buildings were likely erected (Pindar, 1990a,c,d). If the site was indeed used for hundreds of years prior to architectural formalization, stone monumental buildings did not always define ritual activity throughout the site's history; rather, they concretized an intent by the funding source that could have drawn on existing practices and relationships developed over centuries.

The site architecture today sits in ruin, with almost nothing known throughout its long history concerning daily use by local worshippers or ritual events for panhellenic participants. The written record is mostly silent about functional details such as ancient individual and group practices, navigational pathways to and through the sanctuary, spectator seating areas, event staging zones, and the identities of priests. Instead, the only information available – at the level of authorized narrative from what was monumentalized, inscribed, or mythologized – is limited to victors of athletic competitions and ancient rumours or suppositions (Jordan, 2021a,b; Smith, 2012). There are also some unknown physical site parameters. The wild vegetation and possible plantings during ancient times are undocumented; the "sacred grove" to Pan mentioned above by Pausanias stood within the lower sanctuary – was this of note due to the inclusion of special trees or their unique arrangement? Did a grove stand out against a mountain denuded of its native oak forest due to livestock grazing? If there were areas of vegetation in and around the sanctuary, the presence of trees or low shrubs can have a slightly scattering effect on sound transmission, mostly at higher frequencies as shorter wavelengths are scattered by leaf-cover. A more dominant effect would be the sound of wind in the foliage, with different leaves producing a variety of effects (Bolin, 2009).

Some parts of the sanctuary are known to have been free of vegetation: the hippodrome and stadium surfaces, the temenos, and the exposed peak that, though below the tree line, can still be seen from ancient Megalopolis and the surrounding valley. The porosity of the ground without vegetation will have an effect on a sound as it passes across the ground and is partially absorbed across frequency spectra (Suravi, Shin, Attenborough, Taherzadeh, & Whalley, 2019). This dynamic is naturally affected by the water saturation of the ground soil (Horoshenkov & Mohamed, 2006; Oshima, Hiraguri, & Okuzono, 2015), which is a consideration for the site due to the prominence of the hippodrome and temenos for sacred activities on or around these areas. It should be noted that the hippodrome surface today has two distinct material compositions; the majority of its surface is compacted topsoil with limestone fragments from farming activity; however, the southern area is a fine, smoothed gravel introduced since 1973 for historical recreations of the ancient competitions. These have differing acoustic absorption and reflection properties. Other locations where bedrock is covered in soil or where water sources were known to have flowed in antiquity would also have been affected by water saturation levels, and these levels would vary throughout the seasons. Most surrounding hillsides host a combination of exposed limestone bedrock and thin topsoil with low grass cover.

Despite these variables, there is an important structural consistency between ancient and contemporary times on the mountain. The geology of the leeward mountainsides that house the lower sanctuary have remained stable and representative of ancient conditions (Davis, 2009, 2018), suggesting that the experience of sound in the landscape today could bear significant resemblance to what was possible in antiquity when considering the geometry of the landscape. Additionally, sound conspicuously connects disparate locations all around the sanctuary today – activity on the hippodrome can be heard with varying clarity from most (but not all) building outlines, while visible landscape features provide natural amplification for speech in some spots and acoustic masking in others, as discussed later in this article.

Acoustic experience in the present thus becomes a primary research avenue towards understanding how ancient visitors could have organized themselves around ritual practices where sound was a core component. The site itself, landscape and architecture combined, is the most significant source of evidence concerning ancient usage. Given the degree to which the ancient structures and surrounding landscape seem sonically connected today, the acoustics of the sanctuary are approached as a semi-intact stratum of the built landscape, available for the study of ancient site engagement alongside architectural fragments, soil layers, and small finds.

4.2 Sonically Based Research Question, Objectives, and the Standard Field Approach

Our sonic psychoacoustical investigations on Mount Lykaion begin from the understanding that sacred rites and cult practices were originally carried out in the landscape with and without architectural staging. What was considered sacred space in antiquity may be substantially different from today. Moreover, the practices and expectations of visitors were undoubtedly informed by the time period in which they lived and the locality from which they originated; Arcadian/regional cultural traditions, wider political agendas manifesting in Classical and Hellenistic periods, mythological associations between sound and deities (Zeus, Pan, and Pan's nymph Echo, for instance), and even the physical labour of the journey to the site could have exerted strong influence on ancient encounters on the mountain.

Starting from a visual assessment, the original positions of architectural structures are apparent, with many floors at least partially intact. However, original acoustic relationships are generally absent due to the partial, ruined state of structures and the absence of many walls and all roof systems. This dearth prevents studying the effects that building envelopes would have had on acoustic transmission. In many locations, however, it enables the project to study the landscape dynamics that were in place for centuries before the buildings were constructed. Did architectural placement take advantage of latent acoustical properties in the landscape? One can often hear conversations at a great distance with surprising clarity – how much of this (present-day) dynamic is based on the mountainous environment versus the expectations and conditioning from our current industrialized times?

To offer answers to these questions, the investigation aims to simultaneously qualify and quantify the present sonic dimension in relation to antiquity – "qualify" through direct observation, and "quantify" through acoustic measurements and psychoacoustic analysis. Sound is inherently a spatialized experience, and our perception of it brings insight of the environment through which it travelled no matter if the sound originated 1 or 100 m away. Thus, the investigation must be carried out at multiple scales, from a 5 m or less radius of self-originating sound, to tracing acoustics across 100 m or more, to understand the interplay of environment and sound on perception. The study also requires an approach to sonic analysis that combines multiple perspectives, from live voice-testing to recorded impulse responses. In all cases, the study depends on "activating" the acoustics through a newly introduced sound that can then be analysed in detail. A psychoacoustic frame adds to objective measurements (e.g. decibel levels or reverberation times) by turning the focus towards the witnessing individual instead of the sound itself – the research does not stop with a situation's measured decibel level; it goes on to determine how loud the sound is *perceived* to be on average. When applied in historical or ancient settings, psychoacoustic analyses offer a data-driven avenue for considering the daily interactions between ancient users and their surroundings.

The next step is determining where to record. Without direct accounts attesting to ancient design intentions, this inquiry requires the investigation of many possible interconnections based on field observations and informal interviews with participants of the MLESP over the years.

A thorough understanding of the architectural remains and known practices helps to narrow down areas where sound could have played a significant role. Any area that has an obvious entry, orientation, or designated place to sit, for instance, demonstrates a programmed focus of attention and activity – the sonic relationship between the two positions can then be explored. In many cases, the area or activity that is the focus of architectural attention is unclear or unknown, in which case acoustical findings may help to identify potential ancient intentions. For instance, the stoa and seats are built parallel to each other and seemingly parallel to the (naturally occurring) possible processional way – thus the acoustic relationships between these three structures were recorded for analysis. When conducting this work, it is vital to account for any noticeable physical changes since antiquity that alter the sonic dynamics being explored. The entry to the tunnel, for example, has been excavated and currently sits in an open trench almost 2 m below the current ground surface level (Figure 2); any recordings made at this location, no matter how intact the stone architecture of the tunnel may be, will be significantly affected by the earthen trench walls surrounding it. Recordings made here will not be historically illustrative and are omitted from the study.

Figure 2: The excavated (northern) entry to the tunnel, closest to the hippodrome. Acoustic tests here bear no relationship to original conditions due to the high earthen walls on all sides that were formed after site abandonment (Image: P. Jordan).

Another important source of information used to determine recording positions is the prior experience of the author and other archaeological researchers recounting their experience of surprising sonic connectivity while working at the lower sanctuary: the best place to communicate if one's walkie-talkie dies, what positions are completely sonically isolated from the rest of the lower sanctuary, or how far away can one stand and still hear someone on various hilltops (Jordan, 2020, 2021a). These anecdotal observations are then substantiated by extensive *in situ* observation during the field research between at least two researchers.

The best tool for gauging acoustic perception remains the human ear, so live sound-producing and listening tests are carried out before any recordings are made. Each researcher claps her or his hands together several times as a spontaneous impulse response test – though the effect can vary, the intention is not to collect statistically similar data. Rather, the practice is a quickly and easily conducted first draft based on a sound every hearing human is familiar with. It gives preliminary impressions (to the clapper and others) of reverberation patterns, connectivity across the site, and sound localization affordances in that location (the ability of the listener to identify from where the sound and its echoes are originating). Key observations are then followed up with controlled tests. First spoken tests are also carried out during initial explorations, with a researcher speaking a few sentences at a speaking volume for communicating with one person within a 2 m radius, a projected voice (as if speaking in a large room), and a shouted voice designed to carry across at least 50 m. These tests are similar to those carried out by Hamilton and Whitehouse in a different landscape setting (Hamilton et al., 2006; Hamilton & Whitehouse, 2020). The spoken phrases are randomly chosen by the speaker so that the listener does not have the advantage of expectation to subconsciously fill in gaps of misunderstanding or inaudibility. Both adult female and male researchers participated in these first explorations, thus incorporating the inherent sex-dependant variability in human vocal ranges (Lindblom & Sundberg, 2014; Titze, 2000). The tests illustrate how effectively information-rich sonic detail can be transmitted across the sanctuary at different degrees of intention (spoken volume implying a different intended audience from shouting). The language used in these tests is usually English rather than ancient Greek because specific phonemes are not the object of study – the acoustics that defines relationships across the landscape are the core interest, so intelligibility in relation to vocal effort is an important factor in the soundings (Traunmüller & Eriksson, 2000). Systematic speaking tests are later repeated with controlled conditions in positions of interest with a single male voice.

The researchers perform these various tests and note what is heard from her or his perspective. Each individual keeps an ear open for anomalous effects (e.g. surprising speech comprehension at large distances, flutter echoes), alignments between these dynamics and evident architectural features, and other possible patterns. Both the overall connectivity and the character of the soundscape that is activated by the sound tests are noted, as the function and the atmosphere were intrinsically joined in such a sacred space. This fieldwork method works for stationary positions as well as for identifying zones of connectivity or isolation. In the case of zones, a researcher moves along a determined path while carrying out the tests, and the listener notes when sonic dynamics perceptibly change. A clear shift is marked as a different experiential zone; representative points within different zones can then be recorded later.

The concentrated time and attention spent in active listening naturally provides a wealth of site experience and baseline expectations in each researcher. The team homed in on particular research questions during the process. This approach was essential when studying the relationship between the hippodrome surface and surrounding hillsides, for example, where previous experience suggested strong intercommunicative relationships. Multiple zones of varying acoustic connectivity were identified between points by researchers on the surface and adjacent hillsides. After this initial phase of "discovery," recordings were carried out as phase two of research so that the attributes of the different zones could be identified more specifically.

4.3 Integrating Psychoacoustics into Field Research – 2023 Field Applications

Sonic perception guides the field research through planning, execution, and analysis phases of the project. As such, the strategy for recording data at the sanctuary is guided by the intent to compare results (not simply to record the sound of a moment), so that individual experiences of sound can be consistently compared. This takes a number of forms during data collection: the same speaker setup can be recorded in different climatic conditions to trace the consistency of the observed dynamic; a recording can be made between two positions and then the speaker and microphone positions can be reversed for reciprocal analysis; or the recordings of a stationary sound source from two different positions can be compared to each other for variations. But the first phase is *in situ* listening and speaking tests.

Some key positions are naturally identified as being of special research interest by triangulating historical research, architectural signification, and the first phase of field research. The key positions stand out as centrally located, as exceptional in acoustic connectivity, as historically referenced, or as having other relevant features. These positions form central recording nodes from which many other relationships can be explored. One of the nodes identified in 2022, for instance, was a portion of the hillside to the west of the hippodrome surface (see "Hillside" in Figure 1), a position from which spoken conversations could be carried out with an individual on the hippodrome, and which will be returned to later. A speaker is then placed on one of these nodes, and the headset-based microphones record what is heard from one or up to dozens of positions around the sanctuary. Most of these recordings are then repeated with the speaker and microphones switched to determine – among other investigations – if the sonic dynamics are uni-directional or bi-directional in their effects. This detailed recording scheme marks phase two of field investigations.

For these recordings and their comparisons to be scientifically valid, environmental and recording variables are reduced as much as possible or kept consistent during the recorded data collection. The baseline conditions on Mount Lykaion are rural and removed from most constant sources of modern sonic interference; there are no routinely trafficked through-roads in the vicinity, nor are there any developments or inhabitations that could introduce modern sound sources. All recordings were made between 6am and 2 pm for 12 days in August with varying temperature, cloud cover, and humidity conditions, but never during a rain event. August is usually the driest period due to the daytime heat and low rainfall, so moisture contents of the soil is presumed to be lower than other times of year and thus more sound absorptive. Atmospheric

Figure 3: Field assistants Tristan Beutter and Bojan Manasijev setting up the speaker and meteorological testing devices at the southern entrance of the tunnel, which extends downhill to the right (Image: P. Jordan).

conditions were gathered at the speaker's location, including temperature, humidity, atmospheric pressure, wind speed and direction, and position of the measurement device relative to the sun (Figure 3). All these factors can affect sound propagation and perception. At least three recordings of each sound were made to control for interfering sound or changing weather conditions. The same researcher wore the microphones, and the speaker was set to the same height. The researcher wearing the binaural recording device always faced the sound source, and the speaker was always positioned to face the recording position. The sounds of cars, airplanes, and any similar intrusions were omitted (files were re-recorded as needed) to reduce contemporary sonic elements in the data. The ubiquitous sounds of pastoral goat bells throughout the mountain landscape could not be avoided and have been considered a form of living or intangible heritage from more recent eras (Panopoulos, 2018; UNESCO, 2003); however, recording efforts were paused when the auditory masking of the bells overpowered the test signal. Similarly, low levels of wind were a constant factor, but recordings were remade or paused when gusts dominated the recorded material.

Different test signals were employed to cover multiple research motivations. In total, a 10 s long logarithmic sweep file from 100 to 12,000 Hz, a 30 s stepped logarithmic sweep file from 100 to 9,000 Hz, a 20 s white noise file from 100 to 12,000 Hz, and a recording of live speech (male voice) at three different volumes were recorded at each position. The duration and projected volume of each recording signal was designed to maximize the output for analysis while keeping the recording time itself as brief as possible. The ranges of sound were limited to within the capabilities of the speaker and the human hearing range. The human hearing range is widely accepted to be between 20 Hz and 20 kHz; variations exist across individuals and age groups, particularly as one ages and loses sensitivity at higher frequencies (Moore, 2014, pp. 476–477).

Each file offers slightly different information in later analysis during phase three of the field research, so it was important to have multiple sound sources in data collection. The sweeps and white noise files are useful for direct comparisons between files; the most direct version is a transfer function analysis, which traces the effect of the path taken by sound between source and receiver. It allows comparison by amplitudes, for instance, so the difference in decibels (dB) between overall files or portions of signals can be tracked. These findings can then be tallied with psychoacoustic analyses such as perceived loudness to determine if perceived differences correspond with the objective dB readings.[2] The continuous and stepped sweeps provide an easily

2 Perceived loudness is measured in sone, a unit of subjective loudness equivalent to 40 phons. One phon is equivalent to 1 dB(SPL) at 1,000 Hz (1 kHz) and varies at other frequencies. Such rough equivalencies between dB(SPL) and sone can indicate significant deviations between sound behavior and human perception as long as frequency is noted.

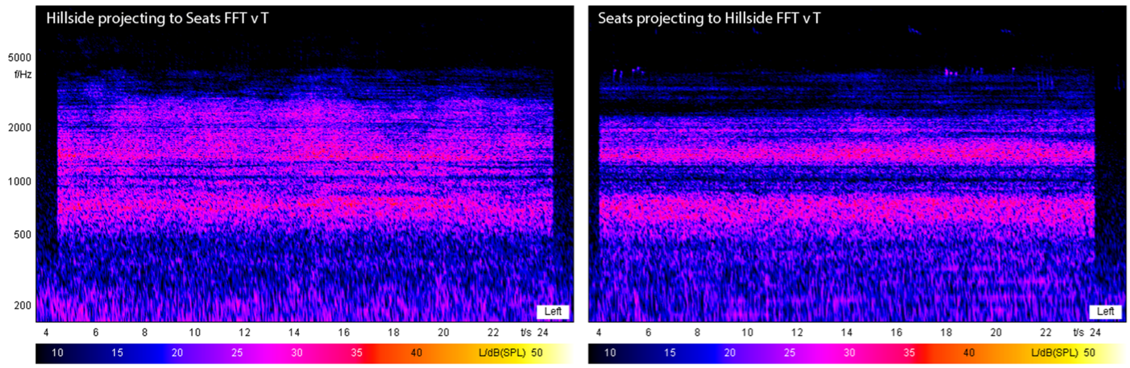

Figure 4: Initial FFT vs time spectrograms comparing identical noise file recordings made between a hillside and the ceremonial seats. In this reciprocal set, the speaker was placed on the hill and directed towards the seats (left) and then placed on the seats and directed towards the hill (right). The right image clearly demonstrates a difference in perception between 900 and 1,200 Hz (Image: P. Jordan using ArtemiS Suite™).

recognizable pattern in fast Fourier transform (FFT) versus time spectrogram representations of the recordings and in psychoacoustic analyses that consider pattern recognition, such as the relative approach (RA) (Bray, 2004; Genuit, 1996). The continuous sweep also allows running convolution analyses with the files later; these, in turn, allow the playback of any sound file as if it had been recorded in the original field setup.

The pre-recorded noise file enables comparisons as well. Because the power of all frequencies (100–12,000 Hz) projected in the file are identical, FFT vs time spectrograms of the recordings reveal any frequencies that are consistently affected by the sanctuary in some way. Figure 4 depicts an example where sound reception is evidently not the same in both directions between the ceremonial seats and a hillside approximately 100 m away (Figure 1 for positions). While the lower range (100–500 Hz) and upper range (4,000 Hz+) in these recordings are attenuated similarly, the range between 900 and 1,200 Hz varies up to 15 dB(SPL) when projecting from the seats vs the hillside. Such a drop could affect the perception of sounds such as human whistling or flute playing in this range such as the aulos (Polychronopoulos et al., 2021). Finally, the live speech recordings are essential for studies in detailed pattern recognition and speech legibility between sanctuary positions, such as lab-based listening studies conducted with public participants. The binaural quality of the recordings is also relevant, for it ensures that later playback has the highest possible experiential fidelity for future researchers – they can be considered archival documents in themselves, beyond the targets of this research project. They also serve as an effective communication tool for general audiences; recordings of live speech offer a humanized approach to the data that are more comprehensible than seemingly abstract sweep files that entail only cursory pattern recognition. The most persuasive tool for sharing sensory research findings to a general audience often can be the field recording itself, where the listener can more easily feel emplaced through a spatialized sonic experience that closely mimics one's own hearing capacities (Fastl & Zwicker, 2007, Chapter 15.4; Genuit & Fiebig, 2017).

4.4 Field Equipment

The basic setup for field recordings has remained constant over four field seasons of recording (2015, 2017, 2019, and 2022): test sounds are emitted from one location and recorded binaurally from another, and meteorological conditions are recorded from only one of the two positions. The equipment used in making field recordings was selected for consistent performance, easy portability, prolonged operation under battery power, and stability in rugged terrain with sunny outdoor exposures. Any external power devices (generators or large power banks) were not employed, as they could introduce potential sonic interference to the recordings in very quiet conditions or with small distances between the speaker and microphones. Recordings in 2022 were made using the handheld SQobold II recording system (HEAD Acoustics, GmbH™) paired with the BHS II binaural headset (binaural microphones worn as headphones), which could also give live sound pressure level readings, FFT-based analyses, and some psychoacoustic measurements such as loudness over time on the SQobold's monitor.

The speaker used to project the pre-recorded sounds was a portable, battery-powered Mackie FreePlay Live speaker, mounted on a standard tripod at human height (the base was positioned at approximately 160 cm/5.25 feet). The test sounds were loaded onto an iPhone 7 with iOS15.5 operating system and then played at maximum phone volume via the Google Drive app, which relayed them to the speaker via Bluetooth. The master volume on the speaker was set to maximum.

Meteorological data were recorded using a Benetech Anemometer (Model GM8910), a Tacklife Humidity Meter (Model HM01), and a WeatherFlow WINDmeter with corresponding Wind and Weather Meter App. The anemometer and humidity meters were affixed to the tripod legs, while the windmeter was handheld and directed towards the wind manually. Since weather conditions may affect sound propagation and perception (Attenborough, 2008; Bohn, 1988), average value readings for the speaker-microphone pairing were taken across the time spent recording all test sounds – a period of approximately 15 min per placement. Any sound emitted from the spinning mechanism of the wind velocity meter was found to be negligible. Generally, recordings were made when the wind was at low or consistent levels.

Recordings were calibrated via a set of control tests made on the hippodrome surface during prime conditions (very low wind and no interfering masking sounds). Each test signal was recorded at 5, 10, 20, and 40 m from the speaker to determine the speaker's output *in situ*.

4.5 Recording Examples

With over 1,600 recordings, the dataset encompasses dozens of site relationships that can be delved into from many perspectives. In order to highlight the constant interplay between perception and archaeological interpretation, two recording examples will be discussed in detail that together demonstrate different scales of interaction and varied applications of psychoacoustics.

Example 1. As mentioned earlier, previous field seasons and anecdotes shared by archaeologists suggested that the hillside immediately west of the hippodrome is a promising place from which to converse with others throughout the lower sanctuary (Jordan, 2020, 2021a). Preliminary field testing confirmed that spoken communication could easily be held across 100 m or more between the hillside and the southern side of the hippodrome. More extensive live testing was first carried out to determine optimal positions from which to make recordings. This process, conducted with three researchers over 2 days, highlighted a specific elevational band on the hillside where speech was clear and intelligible to and from the hippodrome, and where the sound of clapping was sharp and distinct from any first reflections. One position within this band was selected as an indicative study point. In turn, zones of similar features were identified on the hippodrome. It became clear that the hippodrome surface was acting as an effective reflector, though with different intensities across its surface. The ground surface material had a perceptible effect for those on the hippodrome and on the hillside. Indicative points within the contrasting zones were selected as study points for recordings, one of which is depicted in Figure 1 (corresponding to the red dot on the hippodrome).

Identical control recordings were made on the dirt and the gravel surfaces of the hippodrome in open field conditions with a radius of at least 10 m on all sides; these provide baseline absorption and reflection effects of the materials so they may be factored into results later. The psychoacoustic study of all these recordings was started by using specific loudness and the RA analyses (Sottek & Genuit, 2005) to determine if the perceived clarity with which a conversation can be held across these positions is reciprocal or more uni-directional. Such analyses indicate whether the sound level and the perceived loudness levels match, or whether a sound is perceived to be louder than it actually is – a convenient possible effect in this case. From field-tests alone, this location seems strongly reciprocal in its sonic connectivity, an observation that reinforces data from past seasons with similar sensory findings. Without question, there exists a zone on the hillside that is particularly helpful for having a mutual sonic interaction between southern hippodrome activity and hillside. More detailed analysis will provide insight into whether perception and objective sound transmission match or whether human perception is particularly suited to hearing sounds projected between these two areas.

If the observed reciprocity is true, the finding raises the important question of locating ancient spectating as a ritual activity on Mount Lykaion. Chaniotis has made a strong case for ritual activity being an intrinsically and intentionally shared experience between "actor" and spectator (Chaniotis, 2006). In Mount Lykaion's lower sanctuary, cult worship centred around ritualized athletic competitions held in part on the hippodrome surface; public spectators would have completed a pilgrimage up the mountain to witness these events, as they did at other sanctuaries of Zeus such as Olympia and Nemea. Yet no formal areas demarcated for ancient spectating have been found on the mountain in the past decades, suggesting the practical solution that witnesses of the games stationed themselves on the surrounding hillsides. Identifying hillside and hippodrome zones for the optimal perception of activities creates a physical condition to analyse; understanding the role that such experiential reciprocity could have held in ritualized practices, through the research of Chaniotis and others, underscores the possible relevance such effects could have had in ancient practice. Psychoacoustic investigations thus point to a new location for further archaeological examination in search of ancient spectating evidence.

The hillside study point, as mentioned, was identified as a study node for the season, so many reciprocal recording sets across the sanctuary were made from this position in addition to the hippodrome surface. One such additional set was made between the hillside position and the front edge of the stoa, which was open to the north and facing the hippodrome (Figure 1). These two positions have very similar absolute elevations. Field tests suggested that a strong sonic connection existed between both positions, which also share good visual access to the hippodrome. So, recordings were carried out to explore the potential sonic relationships between two possible positions of ancient spectating. With Chaniotis' research again in mind, how sonically connected could groups in these two areas have been?

In favourable conditions, the first analysis showed only a 2–3 dB difference between the two directions of recording (sound from the hillside was slightly more powerful than sound from the stoa). An FFT spectral analysis comparing two recordings from these positions demonstrates the overall finding with slight variations at different frequencies (Figure 5). All recordings from these positions (three in each direction) were compared and the outcome is consistent within a few dB variation. We can then project this result back into historic context; during a ritual athletic festival, celebrants and participants could have been present on the hillside, along the stoa edge, and many locations between these areas. These athletic competitions were popular events, with victors celebrated by writers of the day (Pindar, 1990d; Xenophon, 1922, pt. 1.2.10). Many other activities could have taken place simultaneously, and masking effects from crowds and other

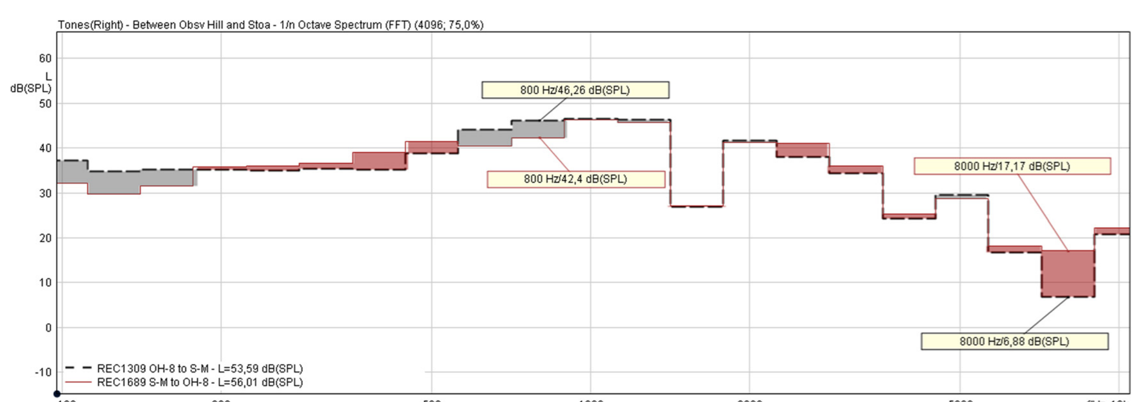

Figure 5: FFT spectral analysis of stepped sweep file projected from the hill (black dashed) and from the stoa edge (red solid). A few dB (SPL) difference are apparent, indicated by colour-related shading and selected spot measurements. (Image: P. Jordan using ArtemiS Suite™).

sound sources throughout the sanctuary would have been likely. Silence may have also played an important role and should not be forgotten. Capacity of connection does not, therefore, guarantee utilization by past users. So, more study is needed to draw more specific conclusions concerning possible interrelationships between groups in these two positions in antiquity.

Example 2. In contrast to the above example, a smaller investigation was carried out in the unearthed ruins of a small building next to the stoa. This is an exception to the typical recordings carried out at the landscape scale, demonstrating how an approach employing psychoacoustics can remain flexible and responsive to different acoustic conditions.

The building (Figure 6) was first documented by the Greek archaeologist Konstantinos Kourouniotes at the turn of the twentieth century (Kourouniotes, 1909) and was again unearthed recently. The structure stands out from other architectural remains in the sanctuary, despite its comparably ruined state, due to its back wall being semi-circular instead of rectilinear. The original curved interior wall is intact up to approximately 1 m in height, with the joints between monumental limestone blocks still tight and the sidewalls extending from each end of the semi-circle moderately intact to the same height. So far, this appears to be the only building with a curved element in the sanctuary, an exception aesthetically and acoustically. Most concave, reflective surfaces will produce a focusing effect for someone positioned at the focus point of the curve, because the rounded surface will reflect more sound back to the source position rather than dispersing it. Such focusing was discussed previously as a probable condition (Jordan, 2021b), and this was confirmed to be present in the 2022 field season.

Making a detailed acoustic study of the ruins, by employing impulse response tests to map out the full acoustic signature of the space, would not provide useful information for this study because the structure in its current form does not represent past conditions. The upper walls, ceiling, roof, and floor are absent, and each would make an important contribution to the acoustics within the structure. Furthermore, the exterior walls of the semi-circular building as well as the adjacent stoa (the remains of which are in the immediate background of Figure 6) and nearby buildings are all missing. All would have mediated the sound entering the inner curved chamber from the exterior of the building. The greater context is simply too different from the supposed original conditions. Inter-sanctuary relationships could thus not be explored through testing, such as where sounds made on the interior of the structure could be perceived throughout the sanctuary. Nor could the perceptual effects be studied directly that are inherent in moving from an open, public place of ritual and transit into a partially enclosed space of more private activity, as guaranteed by the evident architectural design.

Despite the modern alterations, field tests suggested that there was still relevant information to glean: the intact, consistently sized portion of the rounded interior wall lent noticeable focusing effects to both clapping

Figure 6: Excavated building with semi-circular interior stone wall, speaker placed at focal point of curve (Image: P. Jordan).

and spoken tests. So far, this is the only building uncovered at the site with a discernible acoustic character that likely bears a resemblance to original conditions – though they would significantly change the overall acoustics of the interior building volume, fully intact walls, floor, and ceiling would not have likely changed the focusing effects of the concave wall. So, a recording strategy was developed to capture the effects of self-made sounds within the structure rather than relationships between positions in the sanctuary and to determine what role acoustic perception could have played in this unidentified structure.

First, the focus of the concave surface (not quite a 180° semi-circle) was identified and used as the study position (Figures 1 and 6). The speaker was mounted so that the majority of sound emitted would be projected onto the concave surface rather than above it; this required it to be mounted lower than normal at approximately 0.6 m above the floor (Figure 6 shows the "normal" speaker position at 1.2 m, average human height of a modern observer in a standing position). A researcher wore the BHS II headset with microphones and crouched immediately behind the speaker, facing the concave wall and positioned so that the microphones were above the speaker to prevent the speaker box from blocking direct reflections from the concave wall. All pre-recorded and spoken tests were conducted and recorded with this setup to maintain consistency of recording strategy across the sanctuary. In doing so, significant resonance was experienced, with particularly strong results noticed in the field around 1,000 Hz. As expected, repeating the recordings outside of the curve's focus point – on the centreline of the structure at the edge of the building ruins as well as the open ground area beyond – showed that the focusing effect is only perceivable within about a 1.5 m radius from the focus point.

To verify and quantify the above observation of focusing effects, a psychoacoustic analysis was made of the sweep file played in the curve focus point (Figures 7 and 8), comparing a recording made in the semi-circular structure with a control recording made in the free-field condition of the hippodrome at 5 m distance from the speaker. First, an FFT vs time analysis was run on both recordings to determine the absolute levels of sound in each context – how the sound objectively moved through each space. As Figure 7 shows, most of the sound power was conveyed to the microphones with little absorption; the two recordings appear very similar, with the sound power evenly distributed throughout the sweeps. From this representation, we can expect that the sweep is heard clearly across all frequency bands. There is also no indication of unusual resonance around 1,000 Hz in the semi-circular structure, both in absolute terms and in comparison to hippodrome. If this were the only information presented, we might conclude that the two conditions sound the same. However, a representation of the sounds based in a holistic psychoacoustic analysis of each case can provide more nuance based on human perception.

There are a few tools that might accomplish this. The RA tool takes into consideration the many sensitivities of human hearing, with particular attention to our incorporation of pattern recognition and the adaptive

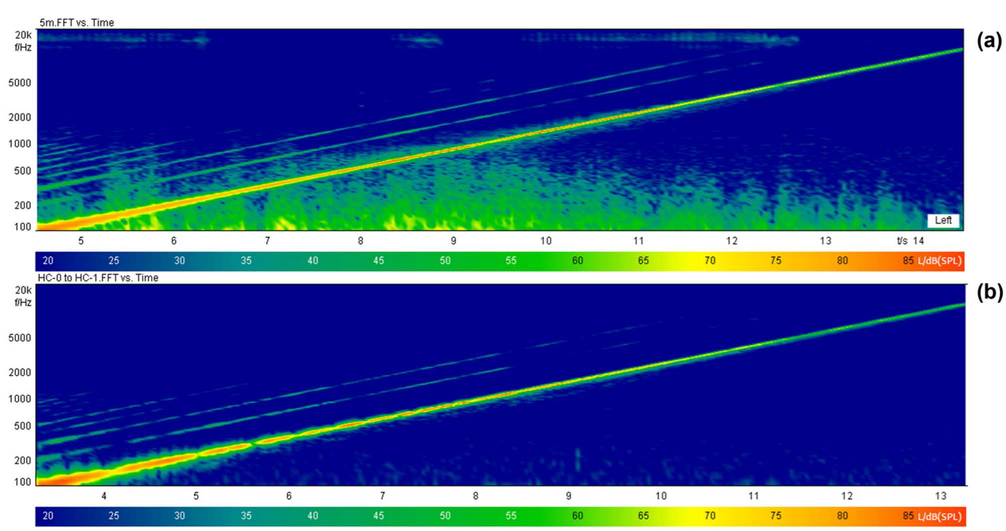

Figure 7: FFT vs time analysis of the sweep file measured at 5 m in the free field of the hippodrome (a), and at the focus of the semi-circular building (b). In both, the sound energy of the sweep (depicted by the well-defined line extending from bottom left to top right) is conveyed quite similarly in both contexts (Image: P. Jordan using ArtemiS Suite™).

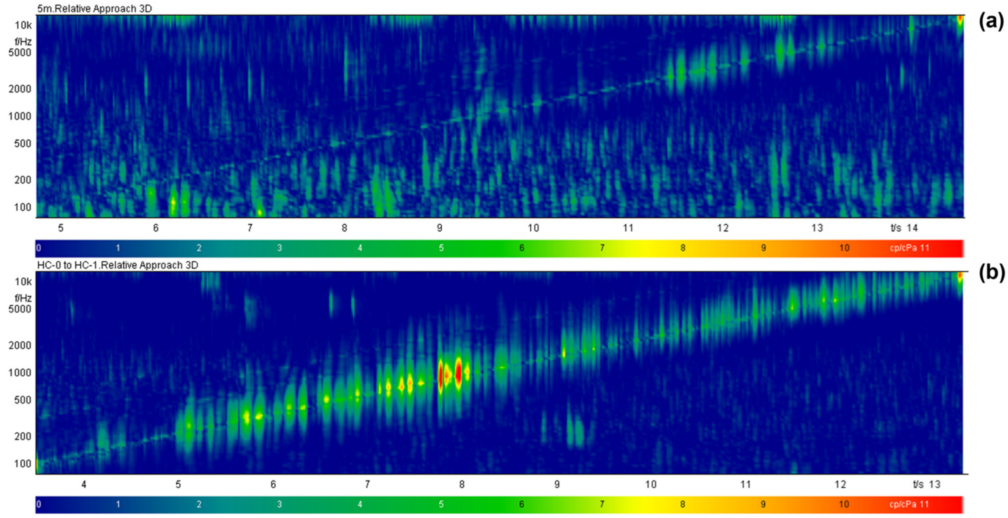

Figure 8: RA analysis of the sweep file representing holistic perception, measured at 5 m in the free field of the hippodrome (a), and at the focus of the semicircular building (b). The sweep is clearly perceived with more intensity in the semi-circular building (b), and the resonance noticed in the field around 1,000 Hz is visible in red (b) (Image: P. Jordan using ArtemiS Suite™).

nature of human hearing (Bray, 2004; Genuit, 1996). For the average listener, absolute sound levels – as depicted in the FFT analysis for instance – are less impactful to perception than how one moment compares to what was heard in the very recent past – especially true given a complex auditory (outdoor) environment when partial masking is present due to other sound sources (Bregman, 1993; Fastl & Zwicker, 2007, Chapter 8). This is an important reason why comparing the subtleties of a sound played once and then repeated even 5 min later is quite difficult, as we would have already adapted to the intervening conditions in between replays and subtly changed our hearing baselines as a result. So the RA analysis (Figure 8) provides a *relative* depiction of holistic perception over time. What can clearly be seen is the difference in perception between the two contexts. On the hippodrome (a), the sweep can be seen (and thus heard) above the background sounds, especially in the upper range between 2,000 and 5,000 Hz. In comparison, the sweep file in the building (b) is perceived to be much stronger at almost all frequencies. This analysis also clearly captures the resonance noticed in the field around 1,000 Hz, shown in red on the image and quantified as falling between 790 and 890 Hz in actuality. So, while the FFT analysis shows the sound energy to be received similarly in both positions, the RA analysis illustrates how the building ruins amplify the perception of that same sound energy and perhaps construct the especially resonant effect between 790 and 890 Hz. The consequences of this effect can be researched in more detail now that it has been identified, perhaps exploring possible ritual sound-making that could occur in this range. Digital modelling has been used productively in other studies of historic conditions (Beckers & Borgia, 2009; Katz et al., 2020; Lokki, 2013; Richards-Rissetto, Primeau, Witt, & Goodwin, 2023; Suárez, Alonso, & Sendra, 2018; Weber & Katz, 2022). A digital reconstruction of the building and acoustic analysis from the same node point could be a future step to expand these findings towards original conditions.

With these *in situ* observations and analyses, we can return to the building as a historic setting to explore their implications at the structure as well as sanctuary landscape level. The original purpose of the semi-circular structure is unknown, but the recordings confirm how personal movements in the space are reinforced in one's own perception, creating a heightened sonic environment distinct from any other part of the sanctuary.[3] This study surmises that such a condition was very likely present in antiquity as well, perhaps

3 Perhaps the only other possibility for such a focusing effect, likely shared with other individuals simultaneously, was the tunnel connecting the building cluster to the hippodrome. Such an effect would have been greatly influenced by the original ceiling treatment of the tunnel; an arched limestone roof would have produced focusing effects, while a flat roof would have simply ensured a closed-off, reverberant space. At present, there is no evidence of a curved limestone roof.

even intensified with the presumed addition of a reflective stone floor and walls. Tests in the semi-circular structure confirmed that the effect would not have been easily shared with other visitors, as one must stand in an unobstructed position at the centre to experience it. Thus, the effect could be understood to be a private sonic reinforcement inaccessible to others, even those at the threshold of the small structure a few metres away. Such sonic dynamics could have been significant if the building originally functioned as a sacred space, especially if sound-making played any role in (ritual) activities within. Sound-based practices were associated with the cult worship of Pan, particularly in caves and grottos (Yioutsos, 2019), and evidence of Pan worship appears to originate on this mountain in the sixth century BCE (Hübinger, 2016, p. 6). A sanctuary of Pan within the ruins of sanctuary of Zeus is referenced by Pausanias and yet to be identified in contemporary investigations: "There is on Mount Lycaeus a sanctuary of Pan, and a grove of trees around it" (Pausanias, 1918, 8.38.5). The curved building does not exactly match this portrayal, but the sonic study allows a different avenue for interrogating contemporary interpretations of Pausanias' description.

Even if not related to Pan, the importance of sonic effect underscored in this structure suggests that the broader sanctuary could have been a more diverse sonic environment than previously understood, composed of numerous forms of sound-based ritual engagement. One would arrive to the ritual space of a rural sanctuary from an established entry point and follow certain necessary activities (purification, initiation rites, etc.). Studying the acoustic relationships in conjunction with the architectural remains allows this order of operations and its impact on ritual practice and site design to be understood more fully. Having the flexibility to study the potentials of sonic perception at the building and the landscape scales is key to understanding the interrelationship of these components.

5 Psychoacoustics and Empathy in Ancient Settings

As the potential ancient sanctuary soundscape emerges, it is natural to imagine ancient individuals hearing what we do today. Our empathetic projections bear a moment of consideration, however, from a few directions. First, it is necessary to recognize that the functional concept of empathy introduces different connotations depending on the disciplinary perspective one takes (Weigel, 2017). This discussion approaches empathy as based on a presumption of shared physiological responses paired with dissimilar cultural contexts – a combination of physical and emotional contexts that we can relate to in a first-person re-imagining (Hollan & Throop, 2022, pp. 1–21, following Halpern, 2001). As such, psychoacoustic tools offer data that reflect this presumed shared physiological response to the sonic environment, but it measures only present conditions. It is then necessary for archaeologists, historians, and other experts to discuss what meanings and values a hypothetical past individual could have ascribed to her or his initial responses to the acoustic environment. The data gathered in the present must be interpreted within the full cultural and emotional context of past users, which we cannot fully know nor ultimately empathize with. In addition, the significant potential in applying psychoacoustics in research must be balanced with awareness of what the tools were originally designed to accomplish. In the case of psychoacoustic measurement tools and spatialized sound more broadly, these can be traced to military research and applications (Ouzounian, 2020, Chapter 5). And as mentioned, the universal applicability of psychoacoustic averages across cultures and settings could still be confirmed to a greater degree.

By applying psychoacoustic analyses to the remains of an ancient soundscape such as on Mount Lykaion, new questions can be asked about the ritual dynamics, possible construction logics, and hierarchies of access that originally organized the site through sound. The examples presented above demonstrate the utility of psychoacoustic analysis as one of many tools: first-hand experience of sonic connection from a hillside was supplemented with psychoacoustic data collection, substantiating the initial observation and leading to new questions concerning spectating as a key element to ritual engagement in ancient times. The tools help speculate about the texture, range, and diversity of sonic input that ancient users could have experienced.

One must take care when drawing conclusions about ancient peoples from such research, however. While psychoacoustic study can draw a direct connection to past actors through a surmised shared perception of sound, it can also be understood to take a universalist or ableist approach to human experience, presupposing an average engagement with sound to be the norm or standard. Its application to archaeological settings then forms the basis for assumptions about past people and their lived experience. A straightforward premise would be that the research delivers a shared, empathetic rendering of experience in the past. Such assumptions have been applied to archaeological investigations already, where "similar perceptual and emotional experiences" are deemed to result in ancient and modern peoples from a similar acoustic condition, with the conclusion that "the effects of soundscape acoustics on human experience are universal in ancient and modern times and listeners" (Valenzuela et al., 2020, p. 6).

Directly relating to the emotional experience of ancient peoples through mechanical innovations must be carefully defined – one cannot presume empathic data as the output of technology developed for other (contemporary) purposes. In fact, the derivation of archaeological interpretations from scientific data has its critics generally (Sørensen, 2017). Modern expectations related to technology, to communication in public, and to sound in isolated spaces are quite strong and deeply influential on conclusions – so while a contemporary visitor hears talking clearly across large distances in the sanctuary and immediately interprets the experience as surprising, this is an interpretive jump that cannot necessarily be ascribed to ancient users as well. Psychoacoustics has been extensively used in researching and predicting emotional responses to contemporary sounds in modern individuals. However, a few more research steps are necessary to draw the line in the reverse direction between current readings and ancient emotional response – the physiological reality of hearing a sound is the same (we should be able to hear the same speech with similar clarity as ancient individuals), but the first emotional response may be vastly different depending on cultural context, for instance. From the archaeological perspective, Joanna Brück warns against forming universal conclusions about phenomenological encounters using contemporary interpretations (Brück, 2005) with parallels found in anthropological discourses on sound-focused research, especially where recording instruments play a vital role (Ames, 2003; Erlmann, 2004; Samuels, Meintjes, Ochoa, & Porcello, 2010). Sarah Tarlow specifically warns against presupposing emotions to be universally defined across time and cultures (Tarlow, 2012), while David Konstan has explored the possible congruity of precognitive emotional response to music in ancient Greece and today (Konstan, 2021). From sound studies, Jonathan Sterne recognizes the tension of what is considered empathy from both sides of the divide between psychoacoustics and humanities/social sciences (Sterne, 2008), a helpful guide to squaring psychoacoustics with emotion-based research within past cultures. Researchers are wise to restrict conclusions about past sensory experience and how it might have been programmed or understood; it is a challenge for upcoming research efforts to actively bridge this current disciplinary disconnect and candidly address how we draw borders between contemporary and ancient responses to the same conditions. In fact, this is a prime window of opportunity for researchers working with sound in the built environment to work towards a common language and interpretation standards. For now, psychoacoustic study clearly proves fruitful for asking richer questions about an embodied distant past and considering more holistic human participation in built environments.

6 Conclusion

Sonic investigations on Mount Lykaion have made one thing clear: sound can be an organizing force to human interaction on the mountain. Applying psychoacoustic approaches to archaeological examinations here enables new kinds of queries concerning how sounded events were perceived in the past by listeners, in addition to how architecture or landscape may have harboured sonic experience. A primary question guiding work on Mount Lykaion is whether the placement of architectural structures took advantage of latent acoustics in the landscape for ritual practice. The evidence is not yet sufficient to say definitively that sonic effect was an intentional driver of the sanctuary's (standing) architectural design. However, the findings substantiate where and to what degree sound could have played a central role in visitor experience. Sonic connectivity between distant people and their activities would have been a prevailing feature in stationary positions and while processing through the sacred terrain. Bi-directional sound clarity between the hippodrome surface and an adjacent hillside points to how easily athletes and spectators could have interacted during festivals. Sonic isolation at the public fountain could have provided experiential contrast from the rest of the lower sanctuary at a moment of more individualized action (drinking, cleansing). And acoustic focusing of the semi-circular building would have provided a sensorial diversity that should factor into considerations of site experience both within and beyond festival celebrations. Further analysis will detail the varied characteristics and locations of this connectivity. It will also overlay the network of positions under relative isolation (e.g. the water sources: the fountain house, Agno fountain, and bath complex) and explore the possible ritual implications with positions of silence and sonic connection being in such close proximity in a sacred landscape for Zeus and Pan.

As capacities in situated acoustic inquiry are only expanding, it is vital that those investigating designed spaces not only familiarize themselves with this technology for use but also be active voices with acoustic engineers in the development of these tools. This is a salient concern as well for those negotiating the fault lines between processual and post-processual approaches to archaeological investigation. The field of psychoacoustics offers helpful approaches for archaeologists probing the experience of past people; the more studies that engage with the difficult challenges such approaches raise, the richer the tools, the theoretical underpinnings, and the research findings can become.

Abbreviations

dB(SPL)	decibel (sound pressure level)
FFT	fast Fourier transform
Hz	Hertz
MLESP	Mount Lykaion Excavation and Survey Project
RA	relative approach

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References

Aletta, F., & Kang, J. (Eds.). (2020). *Historical acoustics: Relationships between people and sound over time*. Basel: MDPI. doi: 10.3390/books978-3-03928-527-3.

Aletta, F., Kang, J., & Axelsson, Ö. (2016). Soundscape descriptors and a conceptual framework for developing predictive soundscape models. *Landscape and Urban Planning*, *149*, 65–74. doi: 10.1016/j.landurbplan.2016.02.001.

Ames, E. (2003). The sound of evolution. *MODERNISM/Modernity*, *10*(2), 297–325. doi: 10.1353/mod.2003.0030.

Attenborough, K. (2008). Sound propagation in the atmosphere. In M. J. Crocker (Ed.), *Handbook of noise and vibration control* (pp. 67–78). Hoboken, NJ: John Wiley & Sons, Inc. doi: 10.1002/9780470209707.ch5.

Beckers, B., & Borgia, N. (2009). The acoustic model of the Greek theatre. In F. M. Mazzolani (Ed.), *Protection of historical buildings: PROHITECH 09, Volume 2* (pp. 1115–1120). Boca Raton: CRC Press.

Blake, E. C., & Cross, I. (2015). The acoustic and auditory contexts of human behavior. *Current Anthropology*, *56*(1), 81–103. doi: 10.1086/679445.

Bohn, D. A. (1988). Environmental effects on the speed of sound. *Journal of the Audio Engineering Society*, *36*(4), 223–231.

Bolin, K. (2009). Prediction method for wind-induced vegetation noise. *Acta Acustica United with Acustica*, *95*(4), 607–619. doi: 10.3813/AAA.918189.

Bray, W. R. (2004). *The "Relative Approach" for direct measurement of noise patterns*. *Sound and Vibration*, September, 20–22.

Bregman, A. S. (1993). Auditory scene analysis: hearing in complex environments. In S. McAdams & E. Bigand (Eds.), *Thinking in Sound: The Cognitive Psychology of Human Audition* (pp. 10–36). Oxford University Press, Oxford.

Brück, J. (2005). Experiencing the past? The development of a phenomenological archaeology in British prehistory. *Archaeological Dialogues*, *12*(1), 45–72. doi: 10.1017/S1380203805001583.

Butler, S., & Nooter, S. (Eds.). (2019). *Sound and the ancient senses*. London: Routledge.

Chaniotis, A. (2006). Rituals between norms and emotions: Rituals as shared experience and memory. In E. Stavrianopoulou (Ed.), *Ritual and communication in the Graeco-Roman world* (pp. 211–238). Liége: Presses Universitaires de Liège. doi: 10.4000/books.pulg.1144.

Davis, G. H. (2009). Geology of the Sanctuary of Zeus, Mount Lykaion, Southern Peloponessos, Greece, and Field Guide. *Journal of the Virtual Explorer*, 33. doi: 10.3809/jvirtex.2009.00242.

Davis, G. H. (2018). *Geologic and geoarchaeological mapping of the Sanctuary of Zeus, Peloponnesus, Greece*. Boulder, CO: The Geological Society of America. doi: 10.1130/2018.DMCH023.

Đorđević, Z., Novković, D., & Pantelić, F. (2019). The ceramic vessels of Trg: Acoustic wall construction in a medieval Serbian Church. *Change Over Time*, *9*(2), 192–212. doi: 10.1353/cot.2019.0011.

Engel, M. S., Fiebig, A., Pfaffenbach, C., & Fels, J. (2018). A review of socio-acoustic surveys for soundscape studies. *Current Pollution Reports*, *4*(3), 220–239. doi: 10.1007/s40726-018-0094-8.

Erlmann, V. (2004). But what of the ethnographic ear? Anthropology, sound, and the senses. In V. Erlmann (Ed.), *Hearing cultures: Essays on sound, listening, and modernity* (pp. 1–20). Oxford: Berg.

Fahlander, F., & Kjellström, A. (2010). Beyond sight: Archaeologies of sensory perception. In F. Fahlander & A. Kjellström (Eds.), *Making Senses of Things: Archaeologies of sensory perception* (pp. 1–13). Stockholm: TMG Sthlm.

Fastl, H., & Zwicker, E. (2007). *Psychoacoustics* (3rd ed.). Berlin, Heidleberg: Springer Berlin Heidelberg. doi: 10.1007/978-3-540-68888-4.

Fazenda, B., Scarre, C., Till, R., Pasalodos, R. J., Guerra, M. R., Tejedor, C., … Foulds, F. (2017). Cave acoustics in prehistory: Exploring the association of Palaeolithic visual motifs and acoustic response. *The Journal of the Acoustical Society of America*, *142*(3), 1332–1349. doi: 10.1121/1.4998721.

von Fischer, S. (2018). Debating volume: Architectural versus electrical amplification in the league of nations, 1926–28. *Journal of Architecture*, *23*(6), 904–935. doi: 10.1080/13602365.2018.1505767.

Fırat, H. B. (2021). Acoustics as tangible heritage: Re-embodying the sensory heritage in the boundless reign of sight. *Preservation, Digital Technology & Culture*, *50*(1), 3–14. doi: 10.1515/pdtc-2020-0028.

Fusaro, G., D'Alessandro, F., Baldinelli, G., & Kang, J. (2018). Design of urban furniture to enhance the soundscape: A case study. *Building Acoustics*, *25*(1), 61–75. doi: 10.1177/1351010X18757413.

Genuit, K. (1996). Objective evaluation of acoustic quality based on a relative approach. *Proceedings of Internoise 1996* (pp. 1–6).

Genuit, K., & Fiebig, A. (2017). Human-hearing-related measurement and analysis of acoustic environments: Requisite for soundscape investigations. In J. Kang & B. Schulte-Fortkamp (Eds.), *Soundscape and the built environment* (1st ed., pp. 133–160). Boca Raton: CRC Press.

Gerstel, S. E. J., Kyriakakis, C., Raptis, K. T., & Donahue, J. (2018). Soundscapes of Byzantium: The Acheiropoietos basilica and the cathedral of Hagia Sophia in Thessaloniki. *Hesperia: The Journal of the American School of Classical Studies at Athens*, *87*(1), 177–213.

Gunderlach, J. (2007). Sound: Exploring a character-defining feature of historic places. *APT Bulletin: The Journal of Preservation Technology*, *38*(4), 13–20.

Halpern, J. (2001). *From detached concern to empathy: Humanizing medical practice*. New York: Oxford University Press.

Hamilakis, Y. (2013). Archaeology and the senses: Human experience, memory, and affect. In *Archaeology and the senses*. New York: Cambridge University Press. doi: 10.1017/CBO9781139024655.

Hamilakis, Y. (2015). *Archaeology and the senses*. Cambridge, UK: Cambridge University Press.

Hamilton, S., & Whitehouse, R. (2020). *Neolithic spaces* (Vol. 1). London: Accordia Research Institute.

Hamilton, S., Whitehouse, R., Brown, K., Combes, P., Herring, E., & Thomas, M. S. (2006). Phenomenology in practice: Towards a methodology for a ‘subjective’ approach. *European Journal of Archaeology*, *9*(1), 31–71. doi: 10.1177/1461957107077704.

Hollan, D. W., & Throop, C. J. (Eds.). (2022). *The anthropology of empathy*. New York: Berghahn Books. doi: 10.1515/9780857451033.

Horoshenkov, K. V., & Mohamed, M. H. A. (2006). Experimental investigation of the effects of water saturation on the acoustic admittance of sandy soils. *The Journal of the Acoustical Society of America*, *120*(4), 1910–1921. doi: 10.1121/1.2338288.

Hübinger, U. (2016). On Pan’s Iconography and the Cult in the Sanctuary of Pan on the Slopes of Mount Lykaion. *The Iconography of Greek Cult in the Archaic and Classical Periods: Proceedings of the First International Seminar on Ancient Greek Cult* (pp. 189–207). doi: 10.4000/books.pulg.204.

International Organization for Standardization (ISO). (2014). *Acoustics – Soundscape Part 1: Definition and conceptual framework*. https://www.iso.org/obp/ui/#iso:std:iso:12913:-1:ed-1:v1:en.

International Organization for Standardization. (2017). *ISO 532: Acoustics – Methods for calculating loudness – Part 1: Zwicker method*. https://www.iso.org/standard/63077.html.

International Organization for Standardization (ISO). (2018). *Acoustics – Soundscape Part 2: Data collection and reporting requirements*. https://www.iso.org/obp/ui/#iso:std:iso:ts:12913:-2:ed-1:v1:en

International Organization for Standardization (ISO). (2019). *Acoustics – Soundscape Part 3: Data analysis*. https://www.iso.org/obp/ui/#iso:std:iso:ts:12913:-3:ed-1:v1:en.

Järviluoma, H., Kytö, M., Truax, B., & Uimonen, H. (2010). *Memory and acoustic environments: Five European Villages revisited*. In N. Vikman & R. Murray Schafer (Eds.). Tampere: TAMK University of Applied Sciences.

Jordan, P. (2020). Sound experience in archaeology and field investigations – an approach to mapping past activities Through Sound at Mount Lykaion’s Sanctuary of Zeus. *Kleos*, *3*, 9–31.

Jordan, P. (2021a). Searching for ancient sonic experience in present-day landscapes. *Archeologia e Calcolatori*, *32*(1), 439–456. doi: 10.19282/ac.32.1.2021.24.

Jordan, P. (2021b). Sounding the mountain: Analyzing the soundscape of Mount Lykaion’s sanctuary to Zeus. In E. Angliker & A. Bellia (Eds.), *TELESTES: Soundscape and landscape at Panhellenic Greek sanctuaries: Vol. VI*. Pisa-Roma: Fabrizio Serra Editore.

Katz, B. F. G., Murphy, D., & Farina, A. (2020). Exploring cultural heritage through acoustic digital reconstructions. *Physics Today*, *73*(12), 32–37. doi: 10.1063/PT.3.4633.

Kolar, M. A. (2017). Sensing sonically at Andean Formative Chavín de Huántar, Perú. *Time and Mind*, *10*(1), 39–59. doi: 10.1080/1751696X.2016.1272257.

Kolar, M. A., Covey, R. A., & Cruzado Coronel, J. L. (2018). The Huánuco Pampa acoustical field survey: An efficient, comparative archaeoacoustical method for studying sonic communication dynamics. *Heritage Science*, *6*(1), 39. doi: 10.1186/s40494-018-0203-4.

Konstan, D. (2021). Being moved: Motion and emotion in classical antiquity and today. *Emotion Review*, *13*(4), 282–288. doi: 10.1177/17540739211040080/FORMAT/EPUB.

Kourouniotes, K. (1909). Excavation of Lykaion. *Praktika*, *64*, 185–200.

Landeschi, G., & Betts, E. (Eds.). (2023). *Capturing the Senses: Digital Methods for Sensory Archaeologies*. Cham: Springer International Publishing. doi: 10.1007/978-3-031-23133-9.

Lenzi, S., Sádaba, J., & Lindborg, P. (2021). Soundscape in times of change: Case study of a city neighbourhood during the COVID-19 lockdown. *Frontiers in Psychology*, *12*. doi: 10.3389/fpsyg.2021.570741.

Lieberman, P. (2007). The evolution of human speech: Its anatomical and neural bases. *Source: Current Anthropology*, *48*(1), 39–66. doi: 10.1086/509092.

Lindblom, B., & Sundberg, J. (2014). The human voice in speech and singing. In T. D. Rossing (Ed.), *Springer handbook of acoustics* (pp. 703–746). New York: Springer-Verlag. doi: 10.1007/978-1-4939-0755-7_16.

Lokki, T. (2013). Sensory evaluation of concert hall acoustics. *The Journal of the Acoustical Society of America*, *133*(5_Supplement), 3489–3489. doi: 10.1121/1.4806177.

McMahon, A. (2013). Space, sound, and light: Toward a sensory experience of ancient monumental architecture. *American Journal of Archaeology*, *117*(2), 163–179. doi: 10.3764/aja.117.2.0163.

Mehrotra, R., Srivatav, P., Mehrotra, U., & Sharma, R. (2020). *Online Journal of otolaryngology and rhinology case report Evolution of Hearing*. San Francisco, CA: Iris Publishers. doi: 10.33552/OJOR.2020.03.000570.

Merleau-Ponty, M. (2004). *The world of perception*. London: Routledge.

Mills, S. (2014). An auditory archaeology. In *Auditory archaeology* (pp. 75–101). Walnut Creek, CA: Left Coast Press.

Moore, B. C. J. (2014). Psychoacoustics. In T. D. Rossing (Ed.), *Springer handbook of acoustics* (pp. 475–517). New York: Springer. doi: 10.1007/978-1-4939-0755-7.

Oshima, T., Hiraguri, Y., & Okuzono, T. (2015). Distinct effects of moisture and air contents on acoustic properties of sandy soil. *The Journal of the Acoustical Society of America*, *138*(3), EL258–EL263. doi: 10.1121/1.4929736.

Ouzounian, G. (2020). *Stereophonica: Sound and space in science, technology, and the arts*. Cambridge, MA: MIT Press.

Panopoulos, P. (2018). Animal bells as symbols: Sound and hearing in a Greek island village. *The Journal of the Royal Anthropological Institute*, *9*(4), 639–656.

Pausanias. (1918). Description of Greece. In S. J. G. Frazer (Ed.), *Perseus*. doi: 10.4159/DLCL.pausanias-description_greece.1918.

Pindar. (1990a). *Nemean Odes, 10.45ff*. The Perseus Digital Library. http://data.perseus.org/citations/urn:cts:greekLit:tlg0033.tlg001.perseus-eng1:9.

Pindar. (1990c). *Olympian Odes, 9.95ff*. The Perseus Digital Library. http://data.perseus.org/citations/urn:cts:greekLit:tlg0033.tlg001.perseus-eng1:9.

Pindar. (1990d). *Olympian Odes, 13.105-111*. The Perseus Digital Library. http://data.perseus.org/citations/urn:cts:greekLit:tlg0033.tlg001.perseus-eng1:13.

Plack, C. J. (2010a). Overview. In Christopher J. Plack (Ed.), *Oxford handbook of auditory science hearing*, Oxford Library of Psychology (2010; online edn, Oxford Academic, 18 Sept. 2012). Oxford, UK: Oxford University Press. doi: 10.1093/OXFORDHB/9780199233557.013.0001.

Plack, C. J. (2010b). Oxford handbook of auditory science: *Hearing, Oxford Library of Psychology* (2010; online edn, Oxford Academic, 18 Sept. 2012). Oxford, UK: Oxford University Press. doi: 10.1093/oxfordhb/9780199233557.001.0001.

Polychronopoulos, S., Marini, D., Bakogiannis, K., Kouroupetroglou, G. T., Psaroudakes, S., & Georgaki, A. (2021). Physical modeling of the ancient Greek wind musical instrument aulos: A double-reed exciter linked to an acoustic resonator. *IEEE Access*, *9*, 98150–98160. doi: 10.1109/ACCESS.2021.3095720.

Primeau, K. E., & Witt, D. E. (2018). Soundscapes in the past: Investigating sound at the landscape level. *Journal of Archaeological Science: Reports*, *19*(February 2017), 875–885. doi: 10.1016/j.jasrep.2017.05.044.

Richards-Rissetto, H., Primeau, K. E., Witt, D. E., & Goodwin, G. (2023). Multisensory experiences in archaeological landscapes – Sound, vision, and movement in GIS and virtual reality. In G. Landeschi, & E. Betts (Eds.), *Capturing the Senses. Quantitative Methods in the Humanities and Social Sciences* (pp. 179–210). Cham, Switzerland: Springer. doi: 10.1007/978-3-031-23133-9_9.

Romano, D. G. (2019). The organization, planning and architectural design of the Sanctuary of Zeus at Mount Lykaion, Arcadia. In E. C. Partida & B. Schmidt-dounas (Eds.), *Listening to the Stones: Essays on Architecture and Function in Ancient Greek Sanctuaries in honour of Richard Alan Tomlinson* (pp. 98–108). Oxford: Archaeopress. doi: 10.2307/j.ctvr00x79.14.

Romano, D. G., & Voyatzis, M. E. (2010). Excavating at the birthplace of Zeus. *Expedition, University of Pennsylvania*, *52*, 9–21.

Romano, D. G., & Voyatzis, M. E. (2014). Mt. Lykaion excavation and survey project, part 1: The upper sanctuary. *Hesperia: The Journal of the American School of Classical Studies at Athens*, *83*(4), 569–652. doi: 10.2972/hesperia.83.4.0569.

Romano, D. G., & Voyatzis, M. E. (2015). Mt. Lykaion excavation and survey project, part 2: The lower sanctuary. *Hesperia: The Journal of the American School of Classical Studies at Athens*, *84*(2), 207. doi: 10.2972/hesperia.84.2.0207.

Samuels, D. W., Meintjes, L., Ochoa, A. M., & Porcello, T. (2010). Soundscapes: Toward a sounded anthropology. *Annual Review of Anthropology*, *39*(1), 329–345. doi: 10.1146/annurev-anthro-022510-132230.

Scarre, C., & Lawson, G. (Eds.). (2006). *Archaeoacoustics*. Cambridge, UK: McDonald Institute for Archaeological Research.

Schafer, R. M. (1994). *The soundscape: Our sonic environment and the tuning of the world* (2nd ed.). Rochester, VT: Destiny Books.

Skeates, R., & Day, J. (2019). The Routledge handbook of sensory archaeology. In R. Skeates & J. Day (Eds.), *The Routledge handbook of sensory archaeology*. New York: Routledge. doi: 10.4324/9781315560175.

Smith, L. (2012). Discourses of heritage: Implications for archaeological community practice. *Nuevo Mundo Mundos Nuevos*. Paris, France: OpenEdition Journals. doi: 10.4000/nuevomundo.64148.

Sørensen, T. F. (2017). The two cultures and a world apart: Archaeology and science at a new crossroads. *Norwegian Archaeological Review*, *50*(2), 101–115. doi: 10.1080/00293652.2017.1367031.

Sottek, R., & Genuit, K. (2005). Models of signal processing in human hearing. *AEU – International Journal of Electronics and Communications*, *59*(3), 157–165. doi: 10.1016/j.aeue.2005.03.016.

Soundscape of European Cities and Landscapes – COST Action: TD0804. (2013). In J. Kang, K. Chourmouziadou, K. Sakantamis, B. Wang, & Y. Hao (Eds.), *Inter-Noise 2013*. Soundscape-COST.

Southworth, M. (1969). The sonic environment of cities. *Environment and Behavior*, *1*(1), 49–70.

Sterne, J. (2008). Being "in the true" of sound studies. *Music, Sound, and the Moving Image*, *2*(2), 163–167. doi: 10.3828/msmi.2.2.11.

Suárez, R., Alonso, A., & Sendra, J. J. (2016). Archaeoacoustics of intangible cultural heritage: The sound of the Maior Ecclesia of Cluny. *Journal of Cultural Heritage*, *19*, 567–572. doi: 10.1016/j.culher.2015.12.003.

Suárez, R., Alonso, A., & Sendra, J. J. (2018). Virtual acoustic environment reconstruction of the hypostyle mosque of Cordoba. *Applied Acoustics*, *140*(May), 214–224. doi: 10.1016/j.apacoust.2018.06.006.

Suravi, K. N., Shin, H. C., Attenborough, K., Taherzadeh, S., & Whalley, W. R. (2019). The influence of organic matter on acoustical properties of soil. *Proceedings of the 23rd International Congress on Acoustics*, 558–565. Berlin: Deutsche Gesellschaft für Akustik (DEGA e.V.).

Tarlow, S. (2012). The archaeology of emotion and affect. *Annual Review of Anthropology*, *41*(1), 169–185. doi: 10.1146/annurev-anthro-092611-145944.

Till, R. (2014). Sound archaeology: Terminology, Palaeolithic cave art and the soundscape. *World Archaeology*, *46*(3), 292–304. doi: 10.1080/00438243.2014.909106.

Till, R. (2019). Sound archaeology: A study of the acoustics of three world heritage sites, Spanish prehistoric painted caves, Stonehenge, and paphos theatre. *Acoustics*, *1*(3), 661–692. doi: 10.3390/acoustics1030039.

Tilley, C. (2004). *The materiality of stone: Explorations in landscape phenomenology*. Oxford: Berg.

Titze, I. R. (2000). *Principles of voice production* (2nd ed.). Iowa City, Ia: National Center for Voice and Speech.

Traunmüller, H., & Eriksson, A. (2000). Acoustic effects of variation in vocal effort by men, women, and children. *The Journal of the Acoustical Society of America*, *107*(6), 3438–3451. doi: 10.1121/1.429414.

Tronchin, L., & Knight, D. J. (2016). Revisiting historic buildings through the senses visualising aural and obscured aspects of San Vitale, Ravenna. *International Journal of Historical Archaeology*, *20*(1), 127–145. doi: 10.1007/s10761-015-0325-2.

Truax, B. (2012). Sound, listening and place: The aesthetic dilemma. *Organised Sound*, *17*(3), 193–201. doi: 10.1017/S1355771811000380.

UNESCO. (2003). *Convention for the Safeguarding of the Intangible Cultural Heritage*. https://unesdoc.unesco.org/ark:/48223/pf0000132540.
Valenzuela, J., Díaz-Andreu, M., & Escera, C. (2020). Psychology meets archaeology: Psychoarchaeoacoustics for understanding ancient minds and their relationship to the sacred. *Frontiers in Psychology*, *11*, 1–9. doi: 10.3389/fpsyg.2020.550794.
Weber, A., & Katz, B. F. G. (2022). Sound Scattering by Gothic Piers and Columns of the Cathédrale Notre-Dame de Paris. *Acoustics*, *4*(3), 679–703. doi: 10.3390/acoustics4030041.
Weigel, S. (2017). The heterogeneity of empathy. In *Empathy* (pp. 1–23). UK: Palgrave Macmillan. doi: 10.1057/978-1-137-51299-4_1.
Westerkamp, H. (2002). Linking soundscape composition and acoustic ecology. *Organised Sound*, *7*(1), 51–56. doi: 10.1017/S1355771802001085.
Wetherell, M., Smith, L., & Campbell, G. (2018). Introduction: Affective heritage practices. In L. Smith, M. Wetherell, & G. Campbell (Eds.), *Emotion, affective practices, and the past in the present* (pp. 1–17). New York: Routledge.
Xenophon. (1922). Anabasis. In C. L. Brownson (Ed.), *Xenophon in seven volumes* (Vol. 3). Cambridge, MA: Harvard University Press.
Yioutsos, N. P. (2014). Pan rituals of ancient Greece: A multi-sensory body experience. In L. C. Eneix (Ed.), *Archaeoacoustics: The Archaeology of Sound: Publication of Proceedings from the 2014 Conference in Malta* (pp. 57–67). The OTS Foundation.
Yioutsos, N. P. (2019). Pan rituals of ancient Greece revisited. In L. Büster, E. Warmenbol, & D. Mlekuž (Eds.), *Between worlds* (pp. 113–135). Cham: Springer Nature Switzerland. doi: 10.1007/978-3-319-99022-4_7.
Yost, W. (2015). Psychoacoustics: A brief historical overview. *Acoustics Today*, *11*(3), 46–53.