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# Modeling Sound in Ancient Maya Cities: Moving Towards a Synesthetic Experience using GIS & 3D Simulation

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Modeling Sound in Ancient Maya Cities: Moving Towards a Synesthetic Experience using GIS  
& 3D Simulation

By

Graham Goodwin

A THESIS

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# Modeling Sound in Ancient Maya Cities: Moving Towards a Synesthetic Experience using GIS & 3D Simulation

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University of Nebraska, 2018

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Digital technologies enable modeling of the potential role of sound in past environments. While digital approaches have limitations in objectively rendering reality, they provide an expanded platform that potentially increases our understanding of experience in the past and enhances the investigation of ancient landscapes. Digital technologies enable new experiences in ways that are multi-sensual and move us closer toward reconstructing holistic views of past landscapes. Archaeologists have successfully employed 2D and 3D tools to measure vision and movement within cityscapes. However, built environments are often designed to invoke synesthetic experiences that also include sound and other senses. Geographic Information Systems (GIS) and Virtual Reality (VR) allow archaeologists to measure and explore the acoustics of ancient spaces. I employ GIS and 3D modeling to measure sound propagation and reverberation using the main civic-ceremonial complex in ancient Copán as a case study. The goal is to create a synesthetic experience to enrich our understanding of the role sight and sound played in ancient Maya cities. For the ancient Maya, sight and sound worked in concert to create ritually charged atmospheres and architecture served to shape these experiences. I use an immersive VR headset (Oculus Rift) to integrate vision with spatial sound and sight to facilitate an embodied experience in order to: (1) examine potential locations of ritual performance and (2) determine spatial placement and capacity of participants in these events.

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## **Chapter 1: Introduction**

### **1.1. Exploration of Sound Through Digital Approaches**

Digital approaches can enrich our understanding of the role and importance of sound in the past by modeling sound in past environments. While digital approaches have limitations in objectively rendering reality, they have the potential to further our understanding of experience in the past because they offer novel approaches to data analysis, integration, visualization, and interaction. To minimize such limitations, we can expand the variables and dimensions of landscapes we analyze; for example, through modeling not only past visibility but also the acoustics of ancient landscapes. Moreover, archaeologists should embrace uncertainty, as no one visualization will ever fully represent the vast number of natural and cultural factors that influenced past behavior. We are modeling past landscapes that are only quantifiable in the present, meaning our visualizations (or simulations) should be more inclusive of sensitivity and uncertainty. However, data is neither neutral nor separate from ideas, practices, contexts, and knowledge. Data exists in relation to those who create it and the affordances of technology influence potential analyses and results.

#### **1.1. Data**

Digital data are a cornerstone of creating new forms of scholarship, publication, outreach, and education. Incorporating a range of data and media formats into a singular environment such as Virtual Reality (VR) or Geographic Information Systems (GIS) enables exploration of space and place in new and innovative ways; however, critical use of digital data is essential (Drucker 2014, Kittler 2006). For example, acoustic modeling of public spaces in ancient Maya cities relies on accurate GIS-based data that improves our ability to generate testable hypotheses.

I follow Kitchin's (2014) definition of data as an unprocessed abstracted element isolated from phenomena. According to Kitchin (2014), data are *capta*, a selective extraction derived from phenomena comprising two categories of data: quantitative and qualitative. Quantitative data are records of physical phenomena; for example, data utilized in visualizations and simulations. Qualitative data is usually descriptive and something that cannot or is difficult to measure such as cultural expressions or the aesthetic qualities of a physical object. Researchers capture data through observation and experiments. Data is also derived through processing or analyses. However, not all data is intentionally created but rather may be the by-product of a system of experiments or research that goes in an unexpected direction or involves new techniques, including digital technologies.

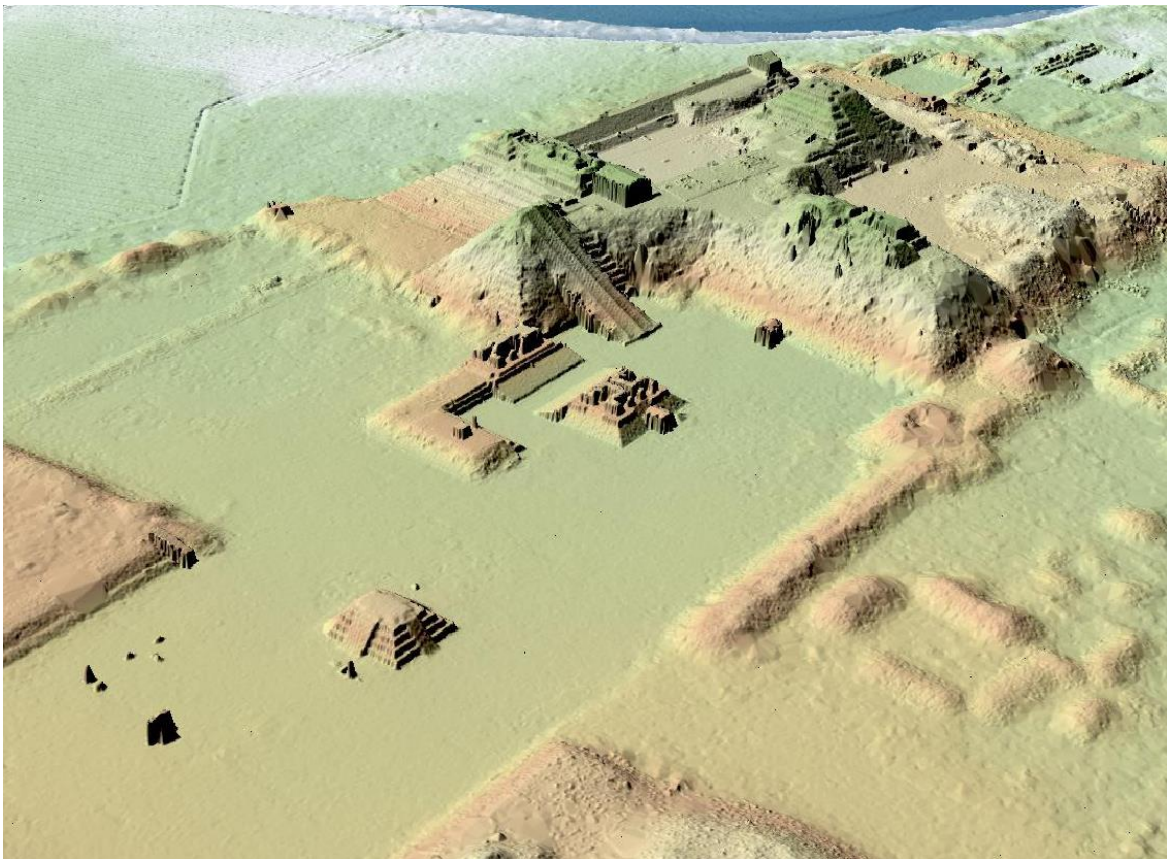
### **1.2. Data and archaeology**

Data management is a major component of archaeological research, both in the field and in the lab. Increasing amounts of data are born digital. Sufficient documentation and curation are necessary to ensure these data are preserved and made accessible in the future (Clarke 2017; Daly and Evans 2005; Richards-Rissetto and von Schwerin 2017). Data are created at all stages of archaeological research: excavation, surveying, and analysis. Often many individuals or teams are involved in gathering data and/or making specific choices in regard to what data are gathered that impact our ability to create digitally-rendered visualizations.

### **1.3. Visualizations**

Until recently, knowledge production has rarely relied on visualizations (Drucker 2014). In my thesis, I create visualizations using GIS and VR to model ancient landscapes that no longer exist or are only partially preserved or understood. Visual knowledge is typically understood in relation to textual and numerical representations; however, digital technologies capable of

rendering landscapes benefit archaeology and provide new methods for visualization and interpretation. Integration of a multi-sensory approach is necessary because our cultural background influences interpretation of knowledge (Drucker 2014). There is also a distinction between visualizations as representation, and visualizations as knowledge generators. Representations are pre-determined and represent existing information, while knowledge generators create new information through use.



**Figure 1.1: LiDAR visualization of Great Plaza, Copán, Honduras (Courtesy MayaArch3D Project)**

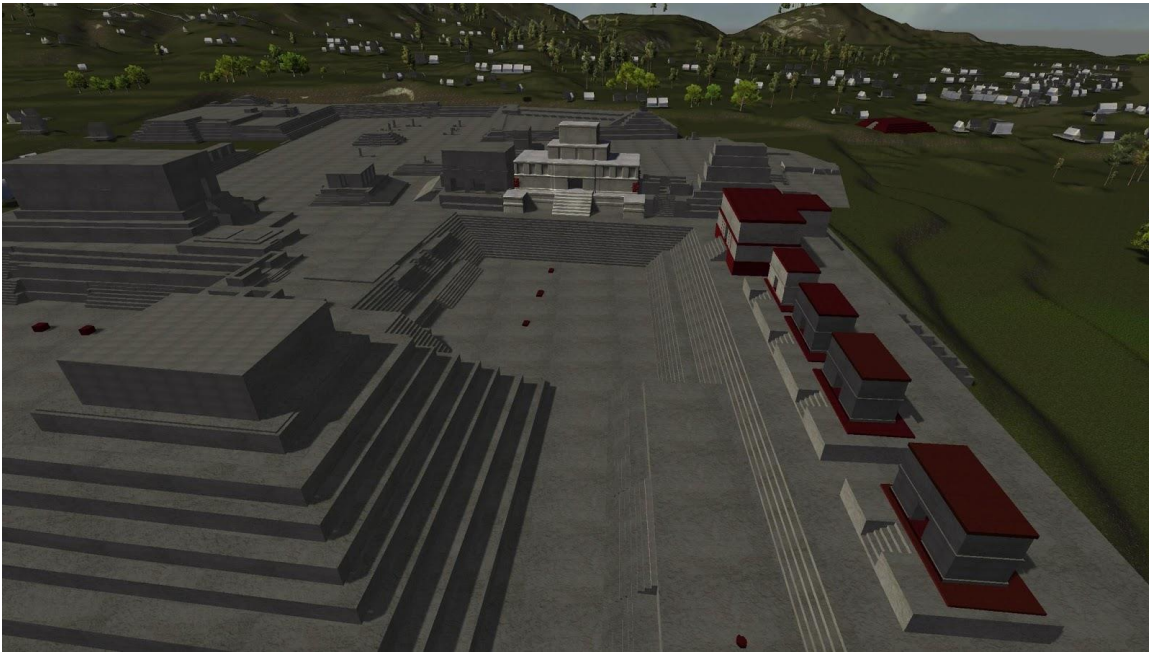
Visualization serves four basic levels of knowledge production according to Drucker (2014). First: modeling of phenomenological experiences through temporal and spatial data; Second: modeling relationships between documents and artifacts; Third: modeling representations of temporality and space found in documents such as narrative; Fourth: modeling interpretations of the other three levels of knowledge production (Drucker 2014). Visual epistemological methods



are a means to spatialize our arguments through graphical means. Visualizations attempt to represent reality objectively, but they are still abstract representations of reality. They present themselves as objective truths but they are static representations of a dynamic reality; however, recent digital tools allow for more dynamic visualizations that are becoming integral to archaeological research (Gupta and Devillers 2017; Llobera 2011).

#### **1.4. Virtual Reality visualizations and archaeology**

Digital visualization methods are much more than simple representations. They are a legitimate analytical tool that can be combined with other technologies, critical thought, and interpretive framework at variable scales. However, the scholarly value of new technology to archaeology depends on its interaction and integration into existing methods of analysis along with the development of new approaches (Daly and Evans 2005).



**Figure 1.2: VR visualization of East Court, Copán, Honduras (Courtesy MayaCityBuilder Project)**

Virtual Reality is an invaluable tool for experiencing archaeological landscapes (Barcelo et al. 2000, Forte 1997, Frischer and Dakouri-Hild 2008, Gillings 1999, and Richards-Rissetto et al.

2012). One important approach uses VR to incorporate an active, mobile, and situated observer into a Geographic Information System (GIS) analytical environment (Richards-Rissetto et al. 2012, 2013) allowing for embodied research based on real-world data (Forte and Bonini 2010). Gillings (1999) argues that multi-sensory perception is active and mobile providing a multi-dimensional interface to engage with past landscapes and the potential is still being realized for exploring the nature of space and time in the past. The archaeological research in this thesis uses VR to better understand and recreate multi-sensory experiences in the past through spatial audio.

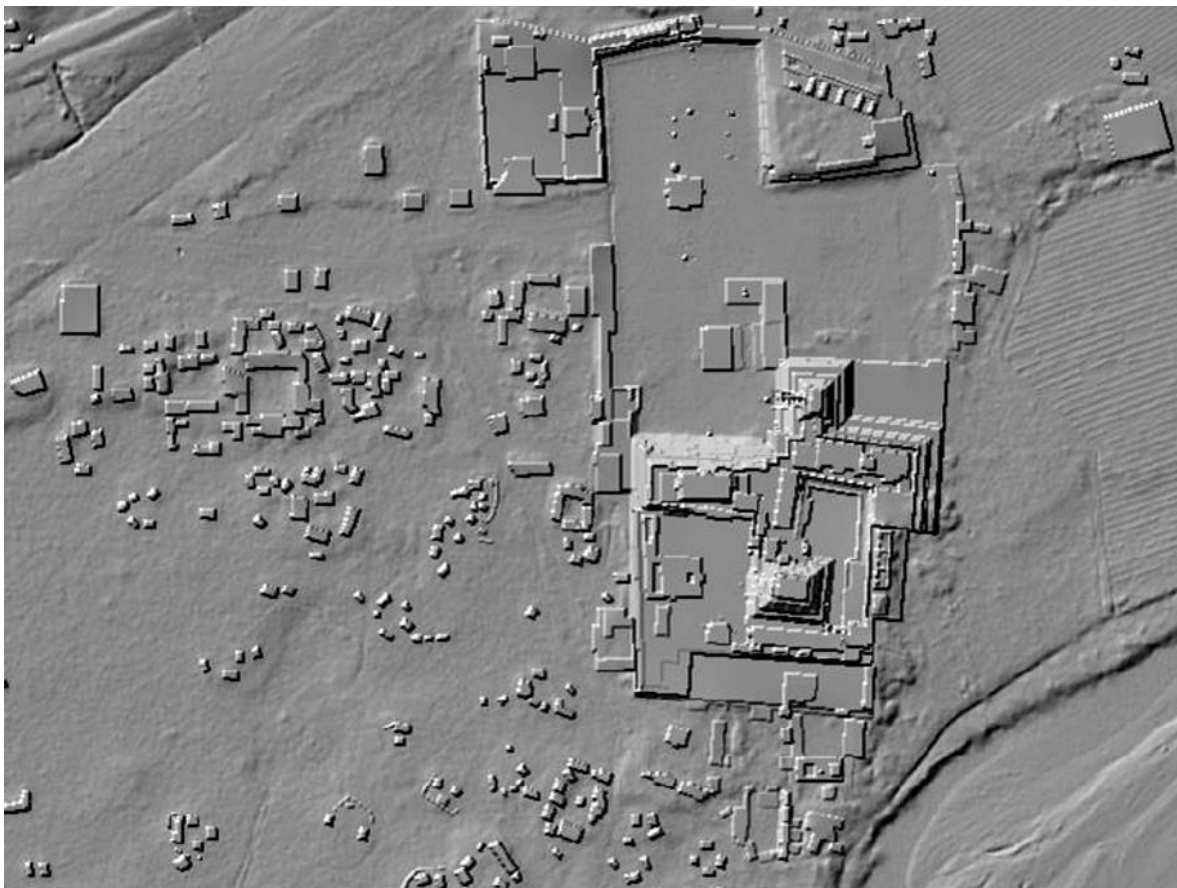
Gillings (1999) also discusses the meaning of VR, and puts forward alternative definitions. The first defines VR as a “manufactured deficiency” that lacks aspects of reality in some way. The second defines VR as a reality that is “intensive” meaning what is visualized may not be fully accurate or even over-exaggerated leading to questions about the authenticity of VR. For Gillings (1999), authenticity is a result of process and a relationship between people and their world and cannot result from manipulations of form. Despite these issues, Gillings (1999) concedes that VR can radically change approaches and interpretations of archaeological data by, for example, offering opportunities to visualize and explore multi-sensory landscapes.

A critical framework for the use of VR exists in the form of cyberarchaeology, which is the integration of GIS, 3D Models, and VR into a single environment for simulation and visualization (Forte 2016). Cyberarchaeology emphasizes interpretation through interaction relying on genetic and cultural triggers to stimulate interpretation. Genetic triggers concern perceptual-motor skills of users, and cultural triggers refer to the ability of users to translate that information into something meaningful. Cyberarchaeology is also concerned with perception as a mediated experience between human understanding and digital models. Thus, in VR, 3D models

act as a catalyst for interpretation and interactive 3D visualizations embedded with sounds of the past allow for multi-sensory representation.

### **1.5. Geographic Information Systems visualizations and archaeology**

Geographic Information Systems (GIS) are one of the primary digital tools for visualization of data in archaeology. The maps created through GIS are defined as outputs of collected data condensed into an intended visualization (Millhauser and Morehart 2016). Archaeologists today have access to a wider array of mapping technologies that differ in theory, data used, formula, outputs, and equipment requirements allowing them to expand their methods. This is a major shift from the early users of GIS in archaeology, who primarily used it for improving site database management, locational analyses, and predictive modeling, which led many early adopters to express concern that GIS would be atheoretical and environmentally deterministic (Allen et al. 1990; Conolly and Lake 2006; Llobera 2001; Richards-Rissetto 2017). More recent approaches are tackling this issue. Current archaeological GIS research is modeling past landscapes using a combination of environmental and cultural variables in order to understand human experience in the past (Howey and Brouwer-Burg 2017). The GIS portion of my thesis addresses this key theme through modeling acoustics using environmental and cultural variables to better understand the role of sound in human experiences of past landscapes.



**Figure 1.3: Urban Digital Elevation Model ca. 800 CE of Principal Group, Copán (H. Richards-Risetto)**

Howey and Brouwer-Burg (2017) comment on the increasing ease of use of GIS and fear of misuse by some researchers. Easy-to-use technology can lead to applications where critical questions cease to be asked, GIS analyses lack conceptual constraints, and methodologies are erroneously applied. Despite these potential shortfalls, GIS offers great potential for investigating cultural processes in the landscape. The case study in this thesis uses GIS to investigate the cross-cultural processes of sound and hearing on the landscape.

One example, relevant to my thesis research, is modeling the potentialities of movement on the landscape that is complimentary to Least Cost Path (LCP) analysis (Howey and Brouwer-Burg 2017; White and Surface-Evans 2012). With digital methods, movement can be understood dynamically rather than statically through combining circuit-based modeling with LCP. Circuit-

based modeling examines how someone “threaded” their way through the landscape, whereas LCP identifies the route from point to point. Circuit-based modeling enables analysis of the probability of movement (intension), and LCP analyzes the constraints created by movement (extension). Howey and Brouwer-Burg (2017) argue that it is vital to understand movement as made up of intension and extension. Because a multitude of possibilities exist before a step is taken, but as the movement begins the possibility for deviation declines. They extend this concept to the cultural landscape, which contains the intension of any number of possible movements and actual physical steps, i.e., extension, come as people move across a landscape, setting off a cycle of information acquisition about the social and ecological variables of the landscape, and layering the landscape with culturally acquired knowledge. Thus, movement is a cross-cultural mechanism that humans employ to organize the landscape that facilitates or restricts movement and interaction in landscapes (Richards-Rissetto 2010; Richards-Rissetto and Landau 2014). Similarly my own research demonstrates how conducive the built Mayan landscape was to ritual performances through hearing and sound. Like movement, hearing is a cross-cultural mechanism humans use to organize the landscape. Archaeologists can employ GIS to investigate the degree to which a landscape was conducive to the flow of social, economic, political, and ideological processes.

### **1.6. GIS and Media Studies**

The evaluation of GIS in archaeology by Howey and Brouwer-Burg (2017) relates to the discussion by Kittler (2006) of new technological innovations in *Gramophone, Film, Typewriter*. Similar to GIS, media challenges how time and space intersect with society. Film and audio can simulate reality but that simulation is different from the real experience. The presentation of film as an objective truth is questionable because it can be cut and spliced. Similarly, GIS simulates

the past landscape but such representations differ from the real or original experience. In the same way that we can chop up film to isolate cross-cultural mechanisms like movement and sound into data distinguishable by minute differences, GIS chops up, and organizes the landscape into visualized layers of data. Additionally, with media and digital technology, trace detection is now possible (Kittler 2006). What was previously unseen or unheard can now be captured as data for analysis. GIS allows for trace detection at the landscape level offering methods to measure the motor and sensory activities of people in landscapes. One approach is through reverse engineering.

### **1.7. Spread-GIS and Reverse Engineering**

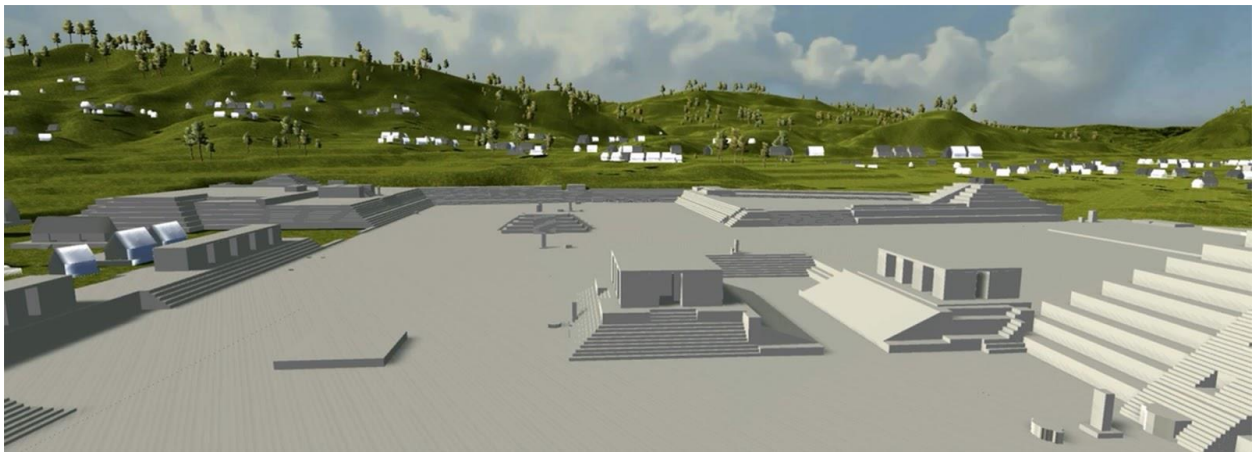
Kittler (2006) argues that the entertainment industry emerged through reverse engineering of military technology, and more generally technology often spreads through reverse engineering, with improvements made through accident and experimentation. Building from this idea, I contend that new approaches to GIS have also emerged in many ways through reverse engineering. Spread-GIS is an open source ArcGIS toolbox for modeling propagation of anthropogenic noise in wilderness settings (Reed et al. 2012) that is one example to support this contention. Reed et al. (2012) reverse-engineered data and calculations from the Acoustic Range Detection Prediction Model (ARDPM) that was developed by United States Army Tank-automotive and Armaments Commands (TACOM). It was created to predict the acoustic detection range of vehicles. On the one hand, ARDPM is a perfect example of what Howey and Brouwer-Burg wanted to avoid in GIS as it is atheoretical and environmentally deterministic. On the other hand, the reverse engineering of ARDPM reflects the changing view of GIS from tool to a process integrated with research methodologies.

### **1.8. Ancient Maya Case Study**

Spread-GIS is an important tool and provides researchers with the ability to investigate the potential role of sound across ancient landscapes that remains understudied. To address this gap, I explore sound and its potential role in shaping human experience in ancient Maya cities. Ancient Maya architecture served as not only spaces for ritual events, but also shaped the experiences of participants and audience. Moving towards an understanding of a Maya sensory experience of spaces is vital for deepening the study of ritual performance and architectural design. For the Ancient Maya, senses invested vitality and meaning to spaces (Houston et al. 2006). In regard to sound, different distances between speakers and audience are associated with different methods of communication that provide information on cultural uses of space (Hall 1968). Among the ancient Maya, data on acoustics can inform on the position(s) of a ruler during ritual events in relation to different audience members offering insight into the role Maya ritual practices played in establishing, maintaining, and transforming social relations. Sound can also be viewed in comparison to existing analyses involving vision and movement, helping to unbind GIS in archaeology from a restricted set of variables. Results can provide information on audience members and their social standing within ancient Maya society. For example, individuals seated within areas of intelligibility may reflect acoustical accessibility or targeting. In regards to intelligibility, I am uncertain as to whether Copán 's ancient inhabitation's all spoke a single common dialect. Hieroglyphic evidence suggests that a common *lingua franca* existed known as Ch'olt'ian was spoken by Classic Maya elites (Houston et al 2001) suggesting that rituals would have been intelligible to a wide array of individuals, even people who were not from Copán such as visiting elites.

My thesis research focuses on the main civic-ceremonial complex at the Ancient Maya city of Copán during the reign of Ruler 13 (695-738 CE). The reign of Ruler 13, known as

Uaxaclajuun Ub'aah K'awiil, coincides with the Late Classic Period (600-822 CE), an important time in Copán's history and the Maya world. Evidence shows that Ancient Maya society was broadly divided into two classes, elite and non-elite. Ruler 13 sat at the top of a stratified hierarchy as ruler of Copán as part of the royal dynasty. Generally, Maya elites were distinguished from non-elite by differences in status, wealth, and power; however, the boundary between elite and non-elite is more of a continuum than a clearly defined boundary (Sharer and Traxler 2006). Uaxaclajuun Ub'aah K'awiil was a great patron of the arts, and oversaw the construction of a number of buildings and monuments. Scholars hypothesize that he overhauled Copán's Great Plaza and placed several stelae within this open, public plaza to form a ritual circuit that he followed in ritual performances. However, he also commissioned one of Copán's most elaborate temples, Temple 22, in the enclosed, private space of the Acropolis. Presumably, the placement of this architecture held significance and shaped the experiences of ancient Maya people. However, what was this experience, and more specifically can we use acoustics to enrich our understanding of ancient Maya ritual performance and architectural design?



**Figure 1.4: 3D simulation of Great Plaza, Copán (Courtesy MayaCityBuilder Project)**

## **2. Chapter 2:**



## **2.1. The Multi-Sensory Landscape**

The landscape, past and present, is a multi-sensorial experience. Anthropologists recognize that all senses are vital for creating meaningful experiences (Rainbird 2008). Landscape archaeology—the study of how people affect and are affected by the landscape around them—requires data or observations. But how can archaeologists “observe” the multi-sensory experience of past people? This is an important question because landscapes change over time, often drastically. Virtual Reality and GIS provide tools and methods to reimagine the experiences of people in past places through computational approaches as well as visual rendering of past archaeological landscapes. Humans often build or modify landscapes to invoke an intentional multi-sensory experience (Lawrence-Zuniga, and Low 2004). Ancient Maya architecture provides an excellent opportunity to investigate the potential of GIS and VR modeling to better understand the role of built environments in creating multi-sensory landscapes. A history of deep scholarship provides data and analyses of artifacts and iconographic evidence that enable a clearer understanding of the Mayan worldview including knowledge about senses (Houston et al. 2006). My thesis case study, the Ancient Maya city of Copán in Honduras, has a long history of survey and excavation with an abundance of data for sensorial and spatial analysis of a past landscape including GIS data and 3D virtual reconstructions (Richards-Rissetto 2010; Richards-Rissetto 2013; Richards-Rissetto et al. 2016; von Schwerin et al. 2017).

## **2.2. Archaeology of the Senses**

Archaeology of the senses is a relatively recent area of research that traces its origins to the 1990s (Fahlander & Kjellstrom 2010). The goal of such studies is to broaden archaeology through examining the past human sensory experiences of sight, hearing, smell, taste and touch

via material culture. Archaeologists need to recognize how senses play into the human experience of interacting with both the external physical world and the internal world of the mind (Fahlander & Kjellstrom 2010). Sight is the sense that tends to be most prominent in archaeological research at the expense of our other senses such as hearing. “Sound is often forgotten in our images of the past although it is often a vital component of any place” according to Fahlander & Kjellstrom (2010: 2). As a result, archaeologists need to consider its role in ancient landscapes. Because meaning, interpretations, and reactions to sound are culturally dependent, I chose to focus on the Ancient Maya because emic data such as hieroglyphs, iconography, and musical artifacts exist to provide a cultural-grounding for interpreting acoustical data.

### **2.3. Sensory Experiences of Landscape**

Senses beyond just vision play an important role in how we interpret the landscape. In his chapter “The Body and the Senses: Implications for Landscape Archaeology”, Paul Rainbirds (2010) considers the body in landscape archaeology including possibilities of incorporating multi-sensorial experiences to understand past landscapes. In his study, Rainbird (2010: 263) notes the body’s focus in landscape archaeology is limited, yet some ethnomusicology studies exist. Steven Feld (1996) investigated the role of sound for the Kalui people of Papua New Guinea and noted that sound directly connected inhabitants to their landscapes. Rainbird (2010) argued that full sensory experiences of landscapes are still in the future; computer technology provides a path toward quantifying and substantiating the past. That future is here.

### **2.4. The Multi-Sensory Built Maya Landscape**

The Ancient Maya intentionally created multi-sensory experience through the arrangement of architecture in their built landscapes (Mongelluzzos 2013). Structures and spaces were not only a

backdrop for activities within Ancient Maya cities, but served to actively influence human experience (Hall 1966; Hall 1969; Moore 1996). While these structures and spaces are now mostly ruins. A georeferenced VR environment models their spatial locations accurately, and restores now missing building materials such as paint, stucco, and plaster. This moves VR environments closer to a more authentic multi-sensory experience (Bartolo, Forte, and Sanders 2000; Forte 1997; Frisher and Dakouri-Hild 2002). By placing an active observer within a specific place, VR avoids the static perspective of maps and photography and creates a richer multi-sensory experience beyond just the visual with spatial sounds (Garner 2018). Mongelluzzo (2013) considers sound as information in VR spaces, a perspective that helps with understanding sensorial goals and perceptions in virtual environments. Sound can be studied quantitatively and empirically when it is considered as information. When this information is reconstructed correctly from geospatial and archaeological data, it can contribute to a more authentic immersive experience within the VR environment. For example, among the Ancient Maya, palaces, ritual and other royal structures served as focal points for visual and acoustic signals, drawing and/or calling the population to royal processions and ritual performances of their rulers (Kurjack 2003). Ancient Maya cities sent multi-sensorial signals that intentionally regulated human movement and actions (Richards-Rissetto 2010, Richards-Rissetto and Landau 2014).

The landscape at Copán contains a variety of structures and spaces within its Acropolis that served as the location for ritual events. These ritual settings become special to the inhabitants through a long history of occupation and repeated ceremonies that invoked sensorial experiences (Hamilakis 2013). The large size of these landmarks served as a symbolic representation of elite power on the landscape. Temples stand out from standard Maya housing not just by their physical size, but also because of their high construction cost and central role in daily life. The

high cost of construction projected social prestige, and elite individuals likely served in managerial positions during construction projects (Kurjack 2003: 281). Their construction and maintenance required a high degree of social organization. Ancient Maya cities regulation of human movement and action affect the distances at which people interact with one another that in turn affects their multi-sensory experience of the landscape.

### **2.5. Proxemics**

Proxemics is an approach to human interaction that analyzes the distances at which humans interact (Hall 1959). It offers a quantitative approach to measure multi-sensorial experience in architecture and landscapes. Proxemics is used to investigate the role of acoustics in a space because of the limitations the human body places on communication over distances. Any interaction between individuals is heavily influenced by their spatial distribution within the landscape. Prior to the invention of mass communication technology, people had to be close to one another to interact (Kurjack 2003: 286). Proxemics allows the identification of zones of experience that are created within spaces that are integral to multi-sensory studies of landscape. Within this framework, the built environment offers archaeologists novel ways to investigate the role and function of physical spaces in shaping ancient experiences.

### **2.6. Conclusion**

Studies of sound are important for recreating the position of an active situated observer in the environment. Humans are spatial beings, and sound in combination with vision provides the context of how they were used together within the environment. Sound propagation and hearing these sounds in a landscape provide an important dimension for thinking about social interaction and the ways in which people understood their place in the ancient world.

### 3. Chapter 3: Recording Ambient Audio for Virtual Reality

#### 3.1. Pre-Fieldwork

On-site measurement is an effective way of gathering data to study the acoustics of archaeological sites. Sound can be studied quantitatively and empirically when considered as information. For my thesis research, I captured the ambient sounds of spaces at Copán with an affordable handheld Zoom H4N stereo recorder with stereo microphones that are adjustable for varying recording situations. Stereo recording also provides useful spatial information and provides a greater sense of position and reality that aids in the creation of an immersive VR experience.



**Figure 3.1: Forward and back view of the Zoom H4N Stereo Recorder**

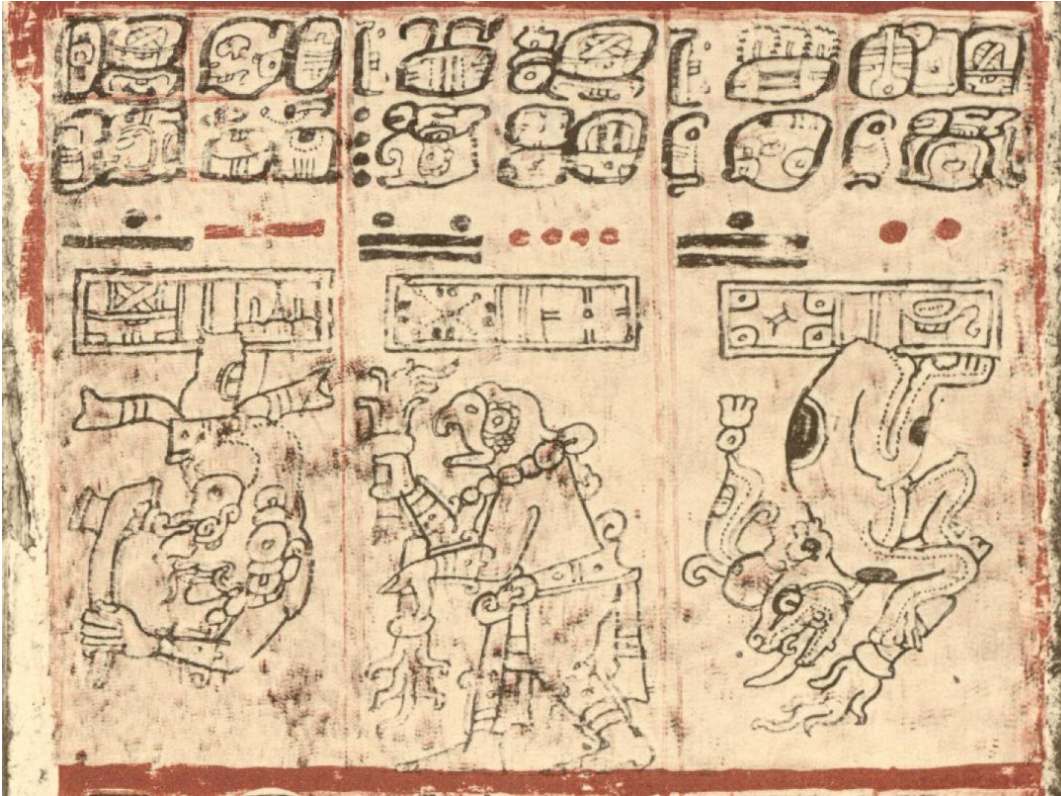
I focused on recording bird vocalizations because birds are a sound source found in both the past and in the current landscape, and birds were important to the Ancient Maya (Anderson 2005). Classic Maya artwork and architecture depicts birds in various contexts (Fash and Fash

1996: 131) and knowledge of birds is widespread among modern Mayan populations (Anderson 2017).



**Figure 3.2: Scarlet macaw marker at Ballcourt A-III, Copán, Honduras (Photo from Wikimedia Commons)**

While many bird species were important to the Ancient Maya, I focused primarily on recording the Scarlet Macaw. Scarlet macaws appear throughout Mayan art, and are still found today at Copán in abundance. Stucco macaw heads are used as ballcourt markers at Copán in the Late Classic Period (Fash and Fash 1996: 131) and several macaws were buried within Structure 16. Stela B in the Great Plaza of Copán depicts Ruler 13 with giant macaws on either side of him (Scherer 2014). Other examples include macaws holding torches in the Dresden and Madrid codices. In the Popol Vuh, the Hero Twins trick the gods of Death by placing macaw feathers on the tips of their un-light cigars to suggest embers. The long-tail feathers of macaws were used for headdresses and clothing, or offerings.



**Figure 3.3: Macaw headed figure in the Dresden codex**

### **3.2. Fieldwork—Capturing Acoustical Data**

I based my fieldwork recording methodology on the principles of Budney and Grotke (1997), which emphasizes a combination of advanced preparation. One of my challenges was tropical birds are difficult to record as they are well-hidden in dense vegetation or located high in the jungle canopy. The goal is to capture bird vocalization with minimal background noise. Because encounters with birds can be unpredictable, I was always prepared to record their vocalizations at the highest possible level without interference from background noise or distortion. For example, I took advantage of terrain to position myself away from undesired background noise. While longer recordings have more potential uses, I found the length of recordings vary significantly by individual bird vocalization. I avoided capturing partial bird vocalizations and tried to anticipate when birds would vocalize. Distance between the microphones and the birds is important, and it

is critical to get as close as possible to the birds when recording. It is also ideal to avoid visual obstructions between you and the bird and body movements must be minimized; even the shuffling of your feet can create significant amounts of noise. Several more steps are necessary before any audio recordings can be brought into the VR environment.

### **3.3. Post-Fieldwork and Lab work**

The captured audio provided the ambient audio in a VR environment (Unity 3D) using the Dear VR plugin. Prior to importing the sounds into the VR environment, I employed the open-source digital audio editor, Audacity, to review and edit the recordings. I selected recordings without the presence of any number of modern noises such as cars as well as excessive noise created by my own body movements to provide the best immersive VR experience. Tracks of varying length were used to create ambience in the VR environment. For example, recorded birdcalls were placed throughout the VR environment, with their audibility relative to user position in the VR environment using DearVR.

Three features of DearVR help simulate audibility relative to the position of a person within the VR environment. The first is occlusion, which is the alteration of sound waves when they are fully blocked by a surface, also known as acoustic occlusion. Second is obstruction, which is similar to occlusion. However obstruction applies only to sound sources close to the user. In addition occlusion affects both sound source loudness and reverberation, while obstruction only affects loudness. Third is distance correction. Distance correction is used to either increase or decrease the perceived distance of a sound source relative to the user. In order to study sound effectively, a basic understanding of the properties of sound is important.

### **3.4. Basics of Sound**



Sound is an audible disturbance of the atmosphere. Sound waves are energy waves that alternatively expand and contract allowing them to be measured and analyzed. The study of sound has a standardized methodology for describing sound quality based on wavelength—the distance from one energy peak to another. Frequency ( $f$ ) is the number of waves completed in one second, and Hertz (Hz, or cycles per second, is the unit of measurement for frequency. Hearing has cross-cultural physiological limitations that set clear boundaries on the sensory experiences of landscape. For example, the range of human hearing is 20 to 20,000 Hz, though most people cannot hear about 16,000 Hz, and humans are most sensitive to frequencies between 500 Hz and 5,000 Hz with a peak between 2,000 Hz and 4,000 Hz, which is the range of human speech (Mills 2014).

Sound wave intensity is measured by decibels (dB). Most sounds resulting from a sounding object produce sound waves of different frequencies at the same time (Mills 2014: 28). Sound with a waveform that repeats at regular intervals has a recognizable pitch. Pitch is a sound attribute that enables a listener to recognize different sounds with identical loudness. Sound pressure level is the effect the power of sound has on its surrounding, most closely associated with loudness.

Sound is a type of sensation. Sensations are relevant to archaeology because humans explore the world through their senses. Knowledge of the world relies on senses and limitations of the senses sets the borders of conscious existence. Sound is often a major component of the initial contact between an organism and the physical environment, as well as vision, and for this reason is critical to landscape archaeology studies. Sight is limited, while hearing is omnidirectional. Sensory stimuli provide data about the physical world and this data gives rise to perceptions of that world to the individual experiencing it. However, human sensation and the perception of

landscape are altered by the imperfect nature of our senses. It is important to identify the cultural factors that affect sensation within a space such as architecture. The individual sensory response may be unique but it is still influenced by a person's culture.

Sensory systems respond to different physical stimulation. Taste and smell respond to chemicals, touch to mechanical pressure, hearing to vibration of air molecules, and sight to electromagnetic radiation. Senses are mostly controlled physiologically, but are culturally and individually affected (Fahlander & Kjellstrom 2012: 3); for example, cultural upbringing and physical health affect how a person interprets sensory experiences, and the cultural aspect of sensations, along with sound localization, plays an important role in my focus on the Ancient Maya.

#### **4. Chapter 4: Ruler 13 Case Study <sup>1</sup>**

##### **4.1. Introduction To Case Study**

The acquisition of large and comprehensive data sets using, for example, airborne LiDAR is changing our perceptions of ancient landscapes, and importantly encouraging fresh lines of enquiry (Chase et al. 2014; Prufer, Thompson and Kennett 2015; von Schwerin et al. 2016). Diverse methodologies employing space syntax, Geographic Information Systems (GIS), and network analysis are used to carry out investigations of ancient cities (Brughmans 2013; Landau 2015; Parmington 2011). Several archaeological analyses have successfully employed 2D and 3D tools to develop computational methods to measure visibility and movement to enrich our understanding of ancient landscapes (Dell'Unto et al. 2016; Llobera 2007; Paliou 2014; Richards-Rissetto and Landau 2014; Richards-Rissetto 2012, 2017; Sullivan 2017). Archaeoacoustics—the study of sound in archaeological contexts—is now becoming more

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<sup>1</sup> Case study presented at 2017 CAA in Atlanta; Paper to be published in 2017 CAA Proceedings

commonplace, particularly to enrich phenomenological approaches (Cross and Watson 2006; Feld and Basso 1996; Helmer and Chicoine 2013; Mlekuz 2004; Rainio et al. 2017; Tilley 1994).

To contribute to this growing body of knowledge, we investigate the question “What roles did sound potentially play in the urban dynamics of ancient Maya cities? As a case study, we employ GIS, 3D modeling, and Virtual Reality (VR) to “measure” acoustics in the main civic-ceremonial complex at the ancient Maya city of Copán in Honduras. Our approach seeks to take advantage of both computational and embodiment methods. The computational component provides quantitative data on sound propagation and reverberation time and the experiential component uses these data to create spatial audio in VR. The two-prong approach involves three components:

- (1) The Spread-GIS toolbox for ArcGIS to calculate noise propagation in Copán’s city center.
- (2) The 3D modelling software SketchUp Pro to calculate building capacity and reverberation time for interior spaces.
- (3) The gaming engine Unity3D and the Dear-VR plugin to create a VR prototype environment with appropriate spatial sound.

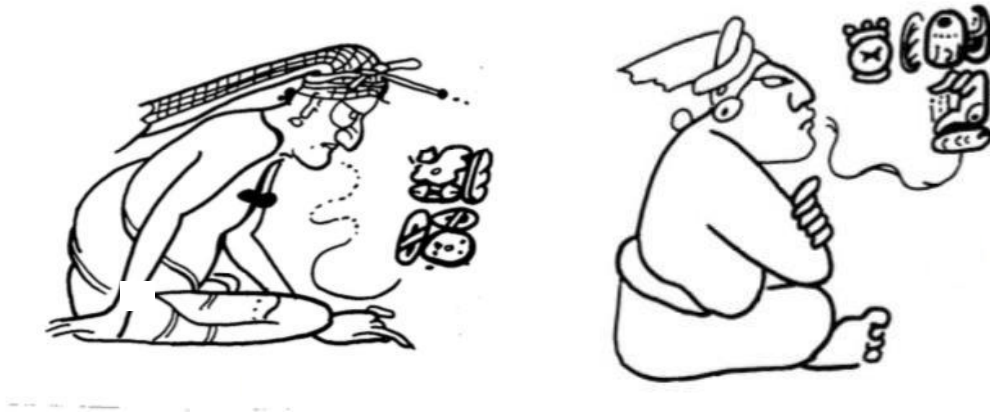
To investigate the potential role sound played in urban dynamics at Copán, we situate the resultant GIS and 3D modelling data within a framework of proxemics—a concept examining the impact of space and distance on human interaction. In regard to sound, different distances between speakers and audience are associated with different methods of communication that provide information on cultural uses of space (Hall 1969; Moore 1996). For example, among the ancient Maya, data on acoustics can inform on the position(s) of a ruler during ritual events in

relation to different audience members offering insight into the role Maya ritual practices played in establishing, maintaining, and transforming social relations. In our case study, we perform preliminary comparisons of acoustics between two locations in Copán's main civic-ceremonial complex—the accessible, public Great Plaza and the restricted, private East Court—two important spaces transformed by Ruler 13 in the early eighth century (Figure 1).

#### **4.2. Ancient Maya Synesthesia – Vision and Sound**

The senses were particularly important in ancient Mesoamerica. The ancient Maya regarded the senses as invisible phenomena that invested life and meaning to spaces. Synesthesia, which is the release of one sensation through another, was integral to the ancient Maya. Visual imagery could lead to sensations associated with hearing. Maya art and architecture was a means of sensory communication as was writing. Evidence suggests scripts were meant to be read aloud, and that writing was a device for vocal readings or performance—thus intricately linking the senses of sight and sound (Houston, Stuart, & Taube 2006).

Sensory organs like eyes were believed to possess a form of agency; sight, illustrated by iconography of projective eyeballs, served a projective role in ancient Maya society—what you saw, affected what you did (Houston, Stuart, & Taube 2006). Visibility studies have been done on regional and city-scale levels in the Maya region illustrating that visibility served as a cultural mechanism to send messages to targeted audiences, establish boundaries, foster social cohesion, and send messages of power (Anaya Hernandez 2006; Doyle et al. 2012; Hammond and Tourtellot 1999; Richards-Rissetto 2010, 2017). While these studies add to our knowledge of experience and interaction among the ancient Maya, they leave out another important sense—sound.



**Figure 4.1: Illustrations of Maya speech scrolls (modified from Houston et al. 2006)**

Speech and song scrolls depicted in ancient Maya artwork communicate the importance and properties of sound. Sound was perceived as something concrete and the whiplash motion in the scrolls may represent the changing volume of speech. Music aroused deities, guided a dancer's rhythm, induced trance through repetition, mimicked animal calls, and enhanced the sensory experience (Houston, Stuart, & Taube 2006). Sound and music were essential components of ritual—songs represented beauty, marked spaces as divine, and communicated information (King and Santiago 2011; Moore 2005). Hieroglyphs often associate deities with music; for example, the storm god Chaak, associated with thunder and wind is linked to song and music. Moreover, echoes or vibrations of sound have been artistically depicted in glyphs, showing an understanding of sensory stimuli (Houston, Stuart, & Taube 2006).

Paintings such as the Bonampak murals depict trumpeters, drummers, and other musicians taking part in processions. Similar depictions are found on a mural fragment from the site of Las Higueras. These murals depict rattlers and flautists closer to their audience and drummers and trumpeters positioned further away, reflecting a sophisticated understanding of musicology where instruments with higher treble should be closer to the audience, while drums and other instruments with higher bass should be placed in the back (Houston, Stuart, & Taube 2006).

Additional archaeological evidence exists in the form of musical instruments including shell trumpets, ceramic whistles, and wooden drums. While musical instruments at the site of Aguateca are primarily found in elite contexts, instruments are also found in non-elite houses suggesting music was not limited to a single social class (Stockli 2014).

The sonorous qualities of raw materials were also important in Mesoamerica. Clays, metals, and precious stones were selected for specific sound and color producing qualities in Postclassic Oaxaca. Moreover, clothing was often embellished with sound producing beads, pendants, and bells (King and Santiago 2011). Together these lines of evidence indicate that sound was an essential component of ancient Maya life, but how did sound work in conjunction with different places, architecture, and material culture to differentially affect audiences, their experiences, and the messages they received?

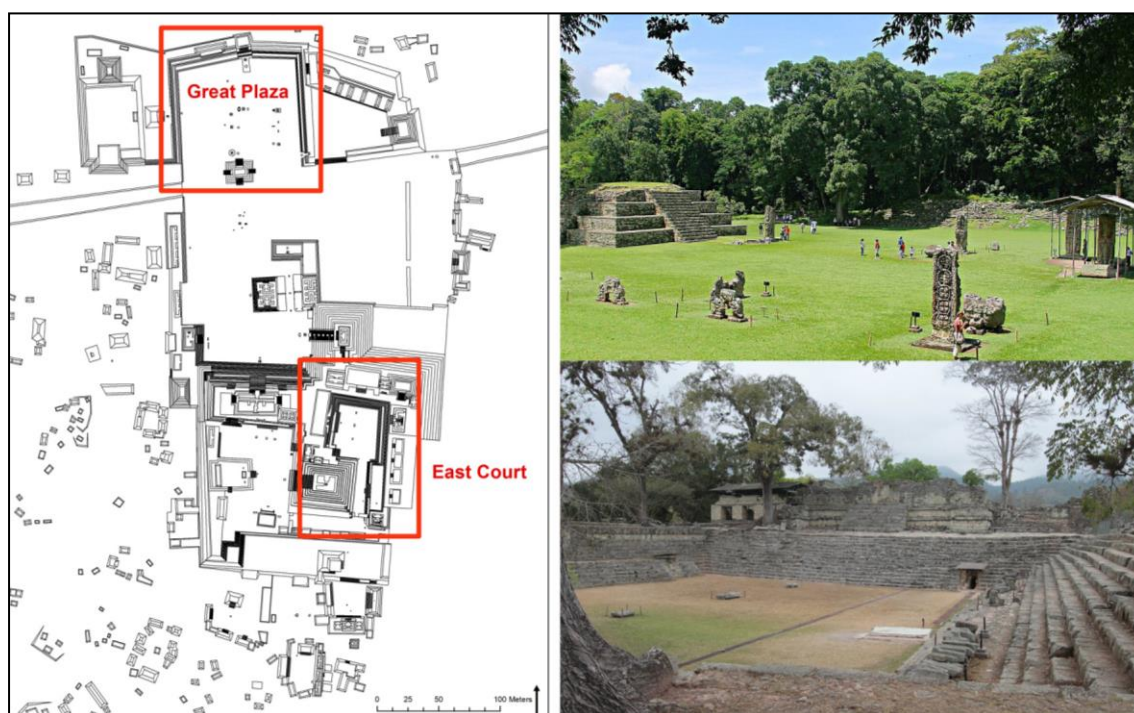
### **4.3. Ancient Maya City of Copán, Honduras**

The case study is the ancient Maya city of Copán —today a UNESCO World Heritage Site— but from the 5<sup>th</sup> to 9<sup>th</sup> centuries it was the center of a kingdom that at its peak covered about 250 square kilometers. Located at the southeast periphery of the ancient Maya world it was an important cultural and commercial crossroad (Bell et al. 2004; Fash 2001). To begin to explore this question of “what roles did sound play in the urban dynamics of the ancient Maya”, we focus on the reign of Ruler 13, *Uaxaclajuun Ub’aah K’awiil*, who ruled the Copán kingdom from 695CE until he was decapitated by a nearby vassal state in 738CE. Ruler 13 is known for introducing high-relief stelae and sculpture to the city. Scholars hypothesize that he commissioned the overhaul of Copán’s Great Plaza erecting several stelae within this open, public plaza to form a ritual circuit that he traversed in public performances (Newsome 2001). He also commissioned one of the city’s most impressive temples, Temple 22, which he placed in

the enclosed, private space of the Acropolis (von Schwerin 2011). Presumably, the differential placement of this architecture held significance and differentially shaped the experiences of ancient Maya people in the eighth century. But, what were these experiences, how did experience differ based on audience, and more specifically can we use acoustics to enrich our understanding of ancient Maya ritual performance and architectural design and ultimately its impact on urban dynamics?

#### 4.4. Methods – Computational and Experiential

To begin to address these questions, we have designed a two-prong methodological approach that is computational and experiential. The computational part uses GIS and 3D modeling to derive quantitative data for acoustical analysis. The experiential part employs immersive Virtual Reality to offer a sense of past experience that involves vision, sound, and bodily movement.



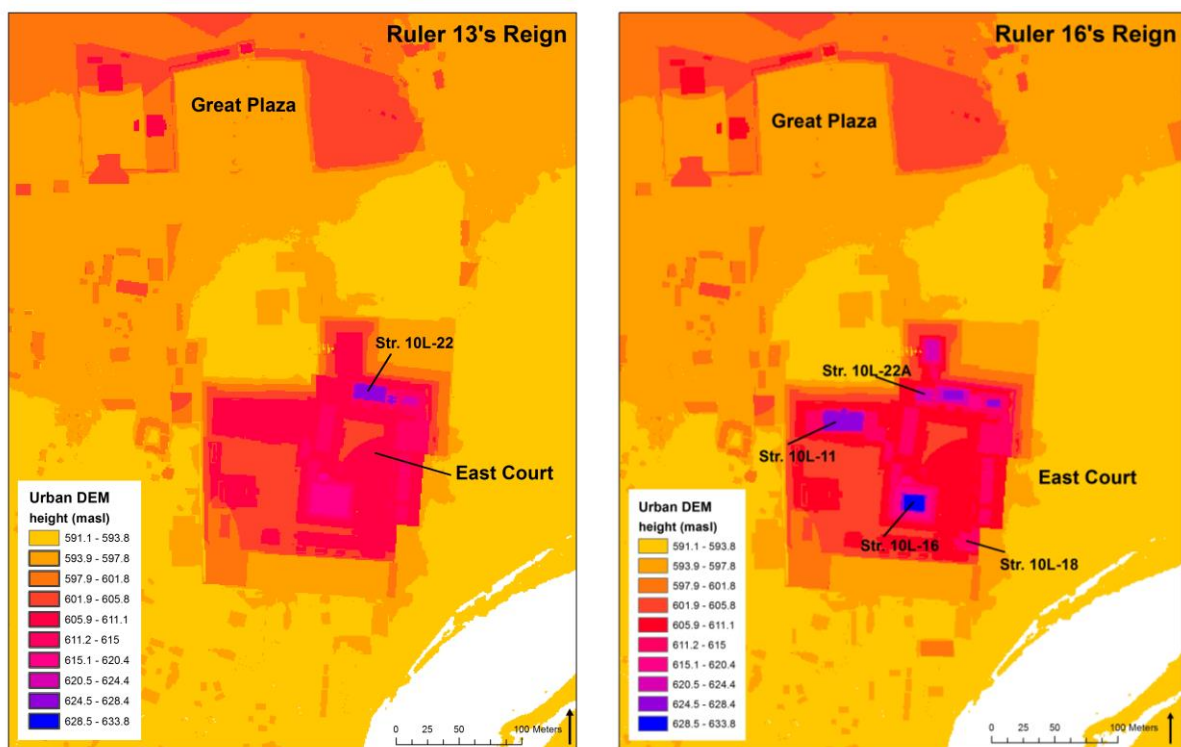
**Figure 4.2: Main Civic-Ceremonial Complex at Copán, Honduras (Great Plaza (top); East Court (bottom))**

Spread-GIS is an open source ArcGIS toolbox (a series of five Python scripts) for modeling propagation of anthropogenic noise in wilderness settings (Reed, Boggs, & Mann 2012). While

the toolbox is primarily used for modeling the effects of noise pollution in ecosystems (Lorig 2016), a few archaeological applications exist. Researchers successfully applied Spread-GIS to calculate sound propagation in Levantine rock art sites in Spain (Díaz-Andreu and Mattioli 2015). In the U.S. Southwest, Primeau and Witt (2017) modified the scripts to create a new Soundshed Analysis tool, which they employed to model the propagation of sound at 33 sites within the Chacoan landscape (New Mexico). However, our approach differs from previous applications in two important ways: (1) we apply Spread-GIS in an urban landscape and (2) we incorporate 3D modeling data of architecture. The ancient Maya are often viewed as practicing urban agrarianism (Isendahl and Smith 2013)—thus, to calculate noise propagation requires a modeling approach that incorporates both ecosystem and urban data, making a modified version of Spread-GIS appropriate. We made minor changes to the Python script to improve output resolution from 100m to 1m (to account for architectural features such as platforms, stairs, etc.), and adjust for syntax and other changes from ArcGIS 9.3 to ArcGIS 10.4.1. Several environmental variables are required to run Spread-GIS. They include: temperature, humidity, wind speed, wind direction, and time of day. We use weather forecasts from Copán Ruinas, Honduras to fill these parameters. Terrain (Digital Terrain Model-DTM) and land cover data (as raster) are also required. The MayaArch3D Project provided a 1m resolution Digital Terrain Model (bare earth) generated from airborne LiDAR (von Schwerin et al. 2016), but the analysis requires an Urban DEM comprising bare earth + archaeological structures. The MayaCityBuilder Project provided a 1m resolution Urban DEM (Richards-Rissetto 2017) representing Copán's archaeological surface during the reign of its final dynastic ruler, Ruler 16, circa 800CE. However, our analysis requires an Urban DEM from the reign of Ruler 13, approximately 50 years earlier circa 750CE. To create this second Urban DEM, we modified the heights of



structures from Copán's main civic-ceremonial complex—removing structures that did not exist (e.g., 10L-18, 10L-22A) and reducing heights of other buildings that existed but were not as tall (e.g., 10L-11, 10L-16). We generated land cover data by combining geological, hydrological, and ecological data into vector data (shapefile) and converting to raster data with the attributes required to run Spread-GIS (Baudez et al. 1983; Fash and Long 1983).



**Figure 4.3: Urban DEM of Copán's main-civic ceremonial complex; (left) East Court structures w/heights for Ruler 13's reign; (right) East Court structures w/heights for Ruler 16's reign**

Sound is produced when an object or substance vibrates and energy is transferred in a wave that alternatively expands and contracts, a cycle that repeats until the energy of the wave has dispersed (Moore 2005). This sound energy is measured by pressure and frequency using decibels and hertz. Decibels measure sound pressure (volume) and hertz measure sound frequency (pitch), or how many times per second the energy wave goes up and down. Objects with less air pressure have lower volume, and objects with a lower hertz (low-pitched sounds)

have waves that go up and down slower and take longer to dissipate. The decibels and hertz of the sound source must also be set in Spread-GIS because, for example, drums vs. a human voice have different sound energy that affects sound propagation.

Spread-GIS has five modules—each module introduces a factor influencing sound propagation and requires data derived in a previous module. A shapefile (point) representing the location(s) of sound sources along with the Urban DEM and Land Cover data are required to run Module 1. Module 1: *spherical spreading loss*- the decline in sound level based on distance from the sound source. Module 2: *atmospheric absorption loss*- the decline in sound level due to air temperature, humidity, and elevation. Module 3: *foliage and ground cover loss*—the decline in sound level due to vegetation and terrain. Module 4: *downwind and upwind loss*- directional changes in sound level due to wind direction, speed, and seasonal conditions. Module 5: *terrain effects*-decline in sound level due to barrier effects from hills or ridge lines. The final output is a floating-point raster dataset that provides data on sound propagation in a landscape setting.

Trimble SketchUp is a user-friendly 3D modelling software that allows users to easily calculate surface area and volume—two measurements essential for calculating reverberation time and building capacity (i.e., number of potential occupants). The first step is to calculate reverberation time. Reverberation time is the time it takes for an echo to fade in a space. It is important for the clarity of speech and music. Too much reverberation and words become muddled, too little reverberation and a person's voice or music will not carry as far (McBride 2014). In ritual contexts, reverberations induce sensation among performers and observers (Hume 2007). Reverberation can aid in detection of otherwise inaudible sounds and help amplify sounds across space (Bruchez 2005). Architectural design directly impacts reverberation because sound is affected by the amount a surface reflects or absorbs sound and the dimension, shape,

and properties of the space in which any given sound is produced (Mills 2014). The calculation requires three parameters: (1) surface area, (2) volume of a space, and (3) absorption coefficients of building materials (how much sound particular materials absorb). The equation is:

$$\text{Reverberation Time (seconds)} = \text{Constant (0.049 for feet, 0.16 for meters)} \cdot \text{Room Volume} / \text{Area Total}^a$$

$$^a \text{Area Total} = \text{Surface Area} \times \text{Absorption Coefficient}$$

**Equation 4.1: Calculation for Total Reverberation Time for Architecture using 3D models**

For absorption coefficients, we used modern equivalents for stone and plaster to represent ancient building materials (McBride 2014). However, absorption coefficients do not remain constant rather they vary by sound frequency, i.e., sound source, and because sound is a wave of energy that oscillates, it is affected by the medium it passes through. Wind, temperature, background noise, reflection, refraction, and diffraction of sound all play a role in the how far a sound travels. Hertz (also referred to as frequency) refers to how many times per second a sound wave moves up and down. A sound with a lower Hertz travels slower, dissipates slower, and tends to travel farther. Decibels (dB) measure the intensity of a sound. A sound with higher decibels is perceived as louder. Frequency of the human voice is typically between 80-500 Hertz (Hz). For this reason we chose to calculate frequency results for 125, 500, and 2000 Hz to cover the range of the human voice and also instruments. And, following Jerry Moore's (2005) we measure intensity using four categories: inaudible (0-10 dB), faint (10-40 dB), moderate (40-70 dB), and loud (70-100 dB) (Table 1).

Subjective Experience	Modern Examples	Map Color and dB Level
Inaudible	10 dB Breathing	White (0-10 dB)
Faint	20 dB Whisper	Yellow (10-40 dB)
Moderate	50 dB Background conversation	Blue (40-70 dB)
Loud	90 dB Jackhammer	Pink (70-100 dB)

**Table 4.1: Intensity measures used for acoustic analysis of subjective experience (based on Moore 2005)**

The second step to calculate reverberation time is calculating the number of people that can fit in a space. The number of people affects reverberation time by increasing the number of potential sound sources, and surfaces for sound to reflect off. The relationship between acoustics and audience size is important because a tightly packed space can hold more people, but leaves less room for dynamic performances such as dancing or processions. Based on Takeshi Inomata's (2006) study of performance and capacity within Maya plazas, we test the impact of number of people on reverberation time for 0.46m, 1.0m, and 3.6m per person.

The main objective of the experiential component is to begin to move beyond simply a visual experience in VR. Knowledge of the world relies on senses, and localization of a person within their environment is enhanced by interactions between auditory and visual sensations (Bruchez 2005, King and Santiago 2011). Spatial audio simulates the spaciousness of sound creating more immersive VR experiences by better situating users within 3D environments. Data from the MayaArch3D and MayaCityBuilder projects are being used to create a VR landscape for ancient Copán (late eighth century) using the gaming engine Unity3D (Day and Richards-Rissetto 2016). Using the Unity 3D platform and Dear-VR, a Unity plug in that simulates human spatial hearing via head-tracking in VR headsets—we are using the Oculus Rift headset to explore the potential of a synesthetic experience to induce a greater sense of embodiment by combining vision, sound, and movement (Fernández-Palacios, Morabito, and Remondino 2017; Forte and Siliotti 1997).

#### **4.5. Results**

This section presents and compares the GIS sound propagation results for the open, public Great Plaza and the enclosed, private East Court to explore the potential role acoustics played

during ritual performances. For the East Court, we also present the 3D modelling reverberation results to further investigate the potential role of acoustics in ritual performance within “enclosed” spaces. Before continuing it is important to define what we mean by audible, and intelligible. We define audible as words being heard but not necessarily understood, while intelligible is defined as the words being understood. The parameters entered into Spread-GIS were:

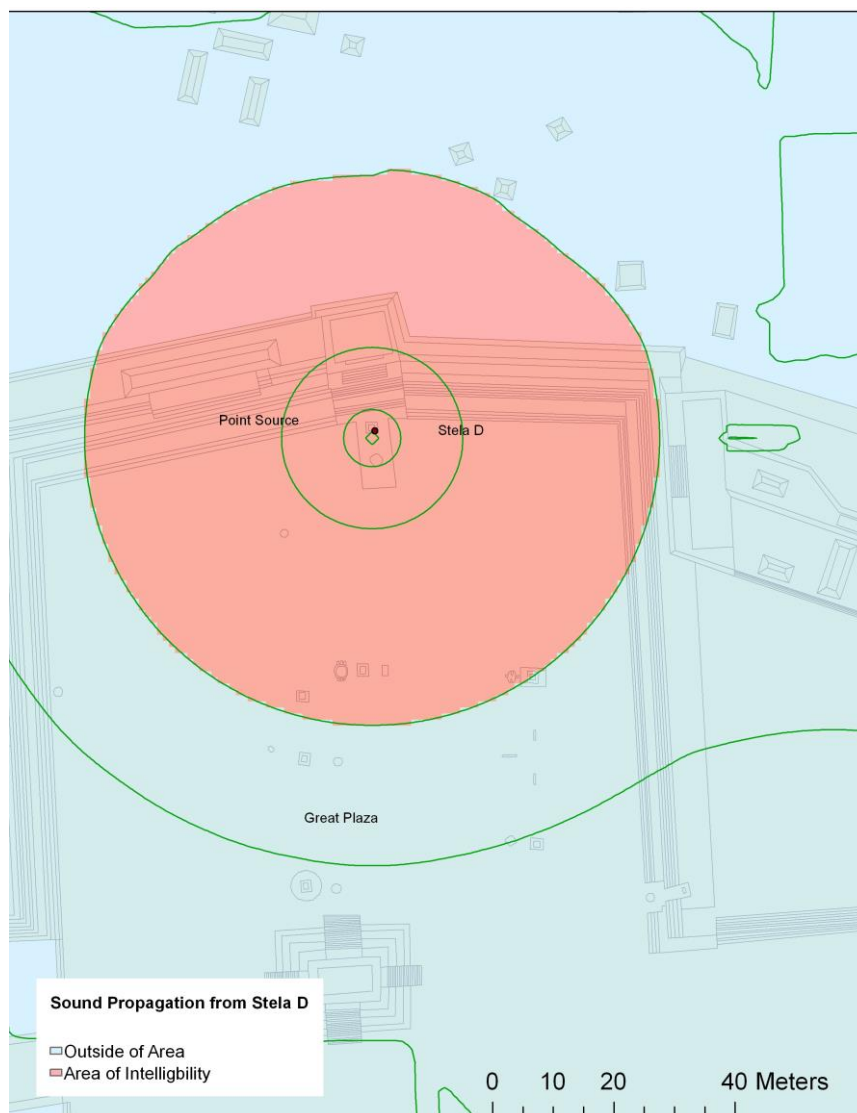
Current interpretations suggest that Ruler 13 began his ritual circuit atop Structure 10L-4—a stepped pyramid that served as a dance platform evidenced by dancing Maize God iconography, and proceeded down the step to process through the Great Plaza’s seven stelae (Newsome 2001). We selected a source point placed at Stela D to represent a location where Ruler 13 might have stood during a ritual procession. Figure 3 shows a raster surface of sound propagation from Stela D. The results indicate that someone speaking at this location would be audible to people sitting on the steps surrounding the Great Plaza Stelae supporting the hypothesis that these steps served as bleachers for an audience (Inomata 2006); but were the speaker’s words intelligible, and if so, from what locations?



**Figure 4.4: Sound Propagation from Stela D, Great Plaza, Copán**

Figure 4.4 illustrates that area of intelligibility from Stela D (based on 60dB or higher). Table 2 compares total audience capacity to number of people able to hear and comprehend a speaker at Stela D. The results suggest that 0.46m per person is ideal spacing to maximize the number of people to directly hear a speaker's words in the Great Plaza; however, regardless of audience size approximately 9% of attendees could decipher a speaker's words. However, this does not mean that Stela D did not serve as an "oration" space for all participants. While the stela served as a visual focal point it would have also been an auditory attraction forming part of complex ritual

performances that spoke to the Maya emphasis on synesthetic experience (Looper 2009). As humans we communicate beyond our voices; visual cues reinforce spoken messages. Moreover, a comparison of visual to auditory results can provide information on audience members and their social standing within ancient Maya society—individuals seated within areas of intelligibility may reflect acoustical targeting so to speak.



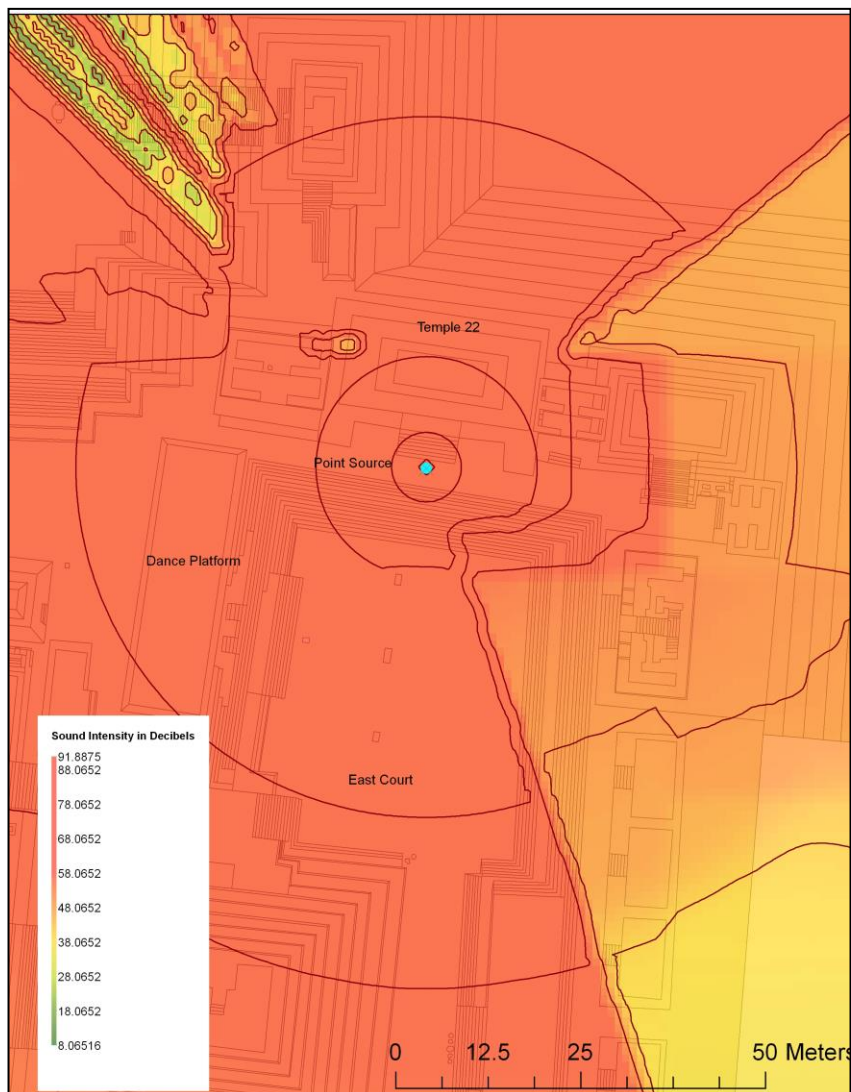
**Figure 4.5: Map highlighting the space in the Great Plaza where speech would be intelligible from Stela D**

Meters per person	Capacity (# people) Great Plaza	# of People Intelligible Speech	% audience (intelligible)
0.46m	27,711	2504	9%
1.0m	12,747	1152	9%
3.0m	3,541	384	9%

**Table 4.2: Comparison of audience capacity to persons able to hear and comprehend speaker from Stela D**

We used the same sound and environmental parameters in Spread-GIS to investigate sound propagation from the steps of Temple 22 in the East Court (Figure 4.6). The Spread-GIS propagation results indicate that a speaker from the steps of Temple 22 could be heard throughout most of the East Court but would likely have to rely on a raised voice, instruments, or visual signals (such as a headdress) in order to send a desired message to the entirety of the East Court (Figure 4.7). The acoustic results support hypotheses that Temple 22, dedicated by Ruler 13 in 715CE, served as a focal point for performance and that the East Court was an exclusive performance space for the elite (Inomata 2006; von Schwerin 2004, 2011). However, because sound, albeit unintelligible, was able to also be heard outside the East Court, the results suggest that others (non-elite) were meant to hear the performance, yet simultaneously be excluded; similar to seeing the highly visible Temple 22 and yet not able to directly access it (Richards-Rissetto 2010, 2017).

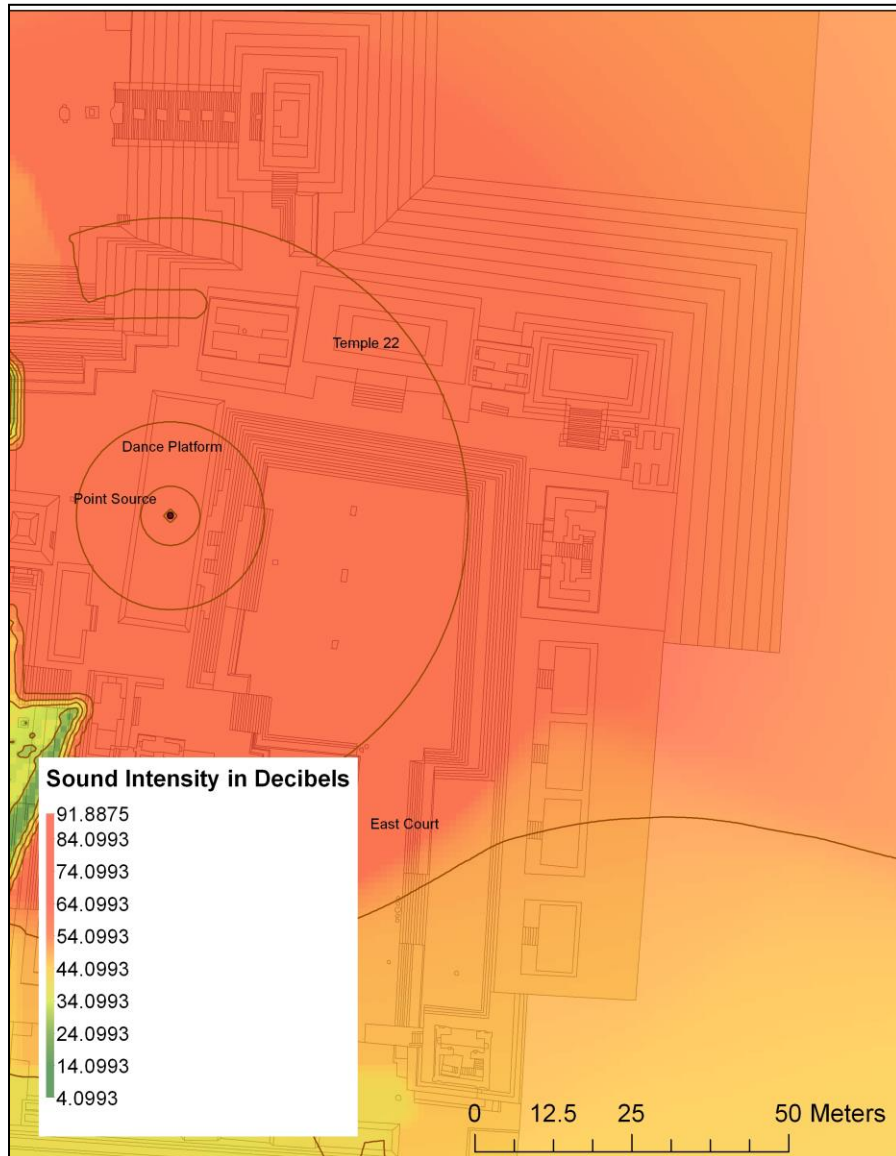




**Figure 4.6: Illustrates Sound Propagation from steps of Temple 22 in East Court, Acropolis**

Figure 4.7 reveals further analysis of East Court acoustics. Propagation results from the elevated Jaguar Dance platform 10L-1 (Looper 2008) suggest that it was an effective platform for vocal performance of in the East Court with a larger soundscape than the Temple 22 stairway. While only some audience members within the East Court could see a performance situated on 10L-1, all audience members in the East Court and many beyond could hear the performance. These results also reinforce differential access to ancient Maya performances—only a small percentage of Copán’s inhabitants could see a performance in the East Court, yet many elite and non-elite could hear it. Together vision and sound were complementary, for some

within the East Court they offered a synesthetic experience, but for others their experience was limited to one sense, i.e. sound, creating differential experiences and sending different messages to “audience” members.



**Figure 4.7: Sound Propagation from Structure 10L-1, East Court, Acropolis**

To further understand the acoustics of the East Court and its potential role in ritual performance, we calculated reverberation time from the East Court. Surface area, construction materials, and number of people in a space affect reverberation time; we used previously

estimated capacities for the East Court (Inomata 2006). Figure 4.8 shows the 3D model in SketchUp used to calculate reverberation times using equation 1 and Table 3 lists calculated reverberation times of the East Court.

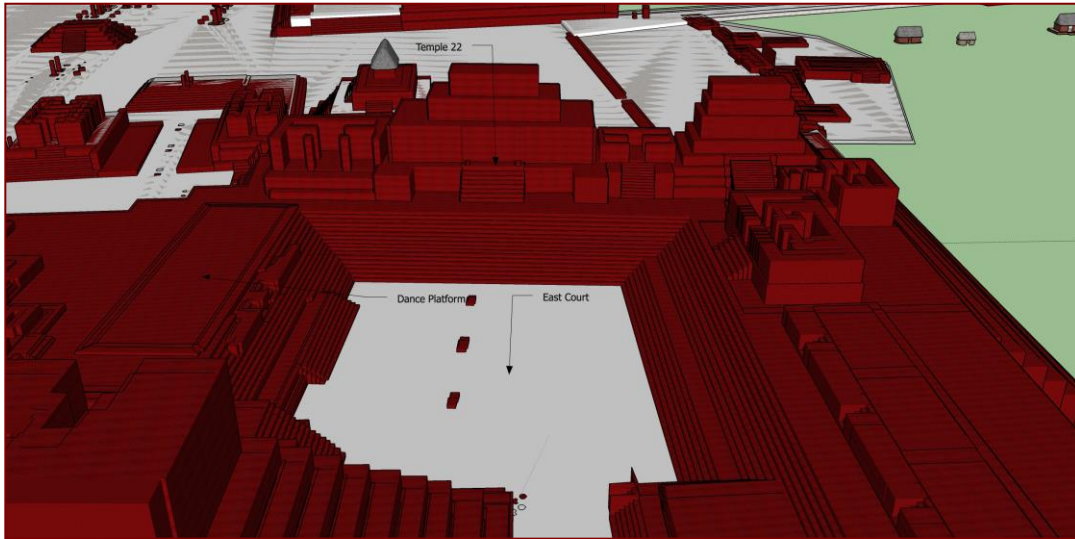


Figure 4.8: 3D Model of East Court from GIS and CAD using SketchUp (Richards-Rissetto 2013)

# of People	Meters per person	Reverberation Time (secs)— 125Hz	Reverberation Time (secs)— 500Hz	Reverberation Time (secs)— 2000Hz
9,641	0.46m	4.97	1.37	1.287
4,435	1.0m	8.42	2.54	2.17
1,232	3.0m	11.23	4.75	3.84
Empty	N/A	12.51	7.51	5.48

Table 4.3: From left to right, reverberation time in the East Court for a sound at 125Hz, 500Hz, and 2000Hz

The results indicate that 1-2 second's reverberation time is ideal for clarity of speech and music; in contrast, at 3-4 seconds there is loss of articulation and difficulty understanding speech (Nave 2017). When the number of people in the East Court is between 0.46 and 1.0 meters per person, sounds at 500Hz, or 2000Hz have reverberation times between 1.287 and 2.54 seconds. It is reasonable to suggest Maya rulers would desire vocal clarity when addressing large crowds

and Maya musicians would desire instrumental clarity when performing; thus, the results indicate that an audience size between 4,435-9,641 persons (based on Inomata 2006) is ideal for ritual performances involving speech as well as musical instruments in the East Court.

## **5. Conclusion to Thesis**

### **5.1. Case Study Conclusions**

Archaeologists increasingly use GIS and 3D modeling to examine vision and movement within landscapes. Few studies investigate the potential role of sound across ancient landscapes. Here, I use the ancient Maya city of Copán in a case study incorporating Spread-GIS, 3D modeling, and VR to explore the role of acoustics in ritual performance and differential audience experience.

Proxemics, a term coined by Edwin Hall (1969) refers to how people use space in communication and categorizes interactions into four separate spatial distances: intimate, personal, social, and public. Researchers hypothesize that the open Great Plaza at Copán served as a performance space for large audiences comprising both elite and non-elite attendees (Fash 2001). While the GIS results supported this interpretation and indicated a speaker could be heard throughout the Great Plaza, my integration of GIS and 3D modeling expands our understanding of the differential audience experience. Initial calculations showed that regardless of audience size, only about 9% of attendees could actually comprehend the words of a speaker at Stela D, a hypothesized performance location along a ritual circuit in the Great Plaza (Newsome 2001). Additionally, the placement of the Great Plaza's seven stelae suggests that movement combined with sound was integral to any performance. Six of the seven stelae are located within 14 to 42 meters of the "bleachers"—the ideal public spatial distance (far phase) for communicating with a large group; only Stela C is outside of this public distance. Thus, as a performer (presumably

Ruler 13) processed through the Great Plaza, the majority of audience members would be “incorporated” within the ceremony. Additional ongoing studies will compare soundsheds to viewsheds to determine if overlap and/or complementarity exist between vision and sound at each of the Great Plaza’s stelae.

Researchers contend that the restricted and enclosed East Court was an exclusive performance space for the elite with Temple 22 and Structure 10L-1 serving as focal points for performance (Inomata 2006; von Schwerin 2004). The distance from the top of the Temple 22 stairs to plaza floor below is 5.5 meters. In proxemics, this distance fits within the public distance, close phase (3.6-7.6 meters) suggesting someone speaking from the stairs is at an ideal distance for addressing a group gathered at the base of the steps. The enclosed courtyard comprising stairs (possibly serving as bleachers) allows a voice to reverberate across the space to extend the impact of a speaker’s voice. 3D modeling results reveal that sound propagation is ideal when audience spacing is between 0.46 and 1.0 meters per person. It is worth noting that, performances atop the Jaguar Platform (Str. 10L-1) on the west side of the East Court could address larger audiences via sound propagation and reverberation. Based on population estimates, approximately 5-10% of the population of Copán could participate in a ritual event held in the East Court. This supports interpretations of this area as a performance space for the elite (Fash 2001). And yet, interestingly, the GIS sound propagation results indicate that people outside of the East Court could hear voices and instruments suggesting that these secluded events, while visually restricted, could still be heard. The fact that voices and music could be heard but not seen could have enhanced elite power by creating an air of mystic.

Theatrical events and politics are closely linked in Classic Maya Society and dynastic rulers benefited from the creation of memory through public ritual (Inomata 2006). While physical

distance is a major factor in the regulation of human interaction and experience, urban design and elements of the built environment also influence social experiences. The placement of temples, plazas, freestanding monuments, stairs, and other built forms regulate interaction by insulating some individuals for small, private affairs and welcoming sizable crowds for other large, public events (Moore 2005). Among the ancient Maya, synesthetic experiences incorporating multiple senses were integral to daily life and ritual performance (Houston et al. 2006). The spatial organization of cityscapes differentially affected human experiences—they were not the same for everyone. Large, open spaces accommodated more people, inviting them to participate in events through sight and sound. In contrast, small, enclosed spaces restricted audience size allowing fewer individuals to witness a performance and yet through sound, others outside of the performance space could still participate. These arrangements could simultaneously send messages of inclusion to the elite as well as to the non-elite of Copán's who can only hear but not see, thus, promoting social cohesion alongside messages of state power and authority.

## **5.2. Conclusions on Digital Approach's to Multisensory Landscapes**

Humans perceive landscapes as a multi-sensorial experience (Bruchez 2007; McBride 2014; Rainbird 2010). Archaeologists use viewsheds in GIS to explore the potential role of vision in past landscapes. Spread-GIS provides a tool for computational analysis that calculates acoustical measurements from spatial data. Virtual Reality also allows researchers to move beyond just the visual to render synesthetic experiences in ancient landscapes that incorporate sound. The combination of these two digital technologies potentially contributes to new interpretations and provides a unique multi-sensual user experience of past landscapes today. My thesis case study using Copán illustrates the powerful role digital technologies can play in understanding Classic

Maya views of the body, sensations, and experiences. While the exact practices of the Ancient Maya are impossible to replicate, documenting the variables that affected sensory experience will enhance and expand our understanding of past landscapes and their inhabitants.

### **5.3. Future and Ongoing Work**

Future and ongoing work is building on the research from this thesis. Now that I have modeled the role of sound, I return to the role of sight in combination with sound. To move closer to modelling a synesthetic experience the complementary roles of sight and sound need to be considered, not just one or the other. Currently, I am working on a collaborative case study that compares changes in the potential role of sound and sight in Copan's Acropolis during the reign of Ruler 13 and the later Ruler 16 (Graham et al. 2018). A key question we are researching is: how does the built environment impact the visibility and acoustics of ritual performance? Future directions for research are in the early stages. One direction is the additional development of the Spread-GIS model to include ecological factors and the impact of building materials on acoustics. Another direction is developing a workflow to bring quantitative acoustic data from GIS into VR. A third and final direction will further explore the role of audience size on acoustics through 3D modeling.

## REFERENCES

- Allen, Kathleen M S, Stanton W Green, and Ezra B W Zubrow. 1990. *Interpreting Space : GIS and Archaeology. Applications of Geographic Information Systems.*
- Anderson, E.N. 2017. "Birds in Maya Imagination: A Historical Ethno-Ornithology." *Ethnobiology* 37 (4): 621–36.
- Barcelo, J.A., M. Forte, and D.H. Sander. 2000. *Virtual Reality in Archaeology.* BAR Intern. Oxford.
- Barcelo, Juan, Maurizio Forte, and Donald Sanders. 2000. *Virtual Reality in Archaeology.* Oxford: ArcheoPress.
- Baudez, CF. n.d. *Introducción a La Arqueología de Copán, Honduras.* Tegucigalpa: Proyecto Arqueológico Copán, Secretaria de Estado en el Despacho de Cultura y Turismo.
- Bell, E, M Canuto, and R and Sharer. 2004. *Understanding Early Classic Copan.* Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology.
- Bodenhamer, David J., Trevor M. Harris, and John Corrigan. 2013. "Deep Mapping and the Spatial Humanities." *International Journal of Humanities and Arts Computing* 7 (1–2): 170–75. doi:10.3366/ijhac.2013.0087.
- Bruchez, M. 2007. "Artifacts That Speak for Themselves: Sounds Underfoot in Mesoamerica." *Journal of Anthropological Archaeology* 26 (1): 47–64.
- Brughmans, T. n.d. "Thinking through Networks: A Review of Formal Network Methods in Archaeology." *Journal of Archaeological Method Theory* 20: 623–62.
- Budney, Gregory F., and Robert W. Grotke. 1997. "Techniques for Audio Recording Vocalizations of Tropical Birds." *Ornithological Monographs* 48 (48): 147–63. doi:10.2307/40157532.
- Chase, AF, DZ Chase, J Awe, JF Weishampel, G Lannone, H Moyes, J Yaeger, and MK Brown. 2014. "The Use of LiDAR in Understanding the Ancient Maya Landscape." *Advances in Archaeological Practice* August: 208–21.
- Conolly, James, and Mark Lake. 2006. *Geographical Information Systems in Archaeology. Cambridge Manuals in Archaeology.* doi:10.1017/CBO9780511807459.
- Cross, I, and A Watson. 2006. ". Acoustics and the Human Experience of Socially Organized Sound." *Archaeoacoustics*, 107–16.
- Cummings, V. 2010. "Virtual Reality, Visual Envelopes, and Characterizing Landscape." In *Handbook of Landscape Archaeology*, edited by W. A. Congress and B.D. Thomas, 285–91. Walnut Creek: Left Coast Press.
- Day, Z and, and H Richards-Rissetto. 2016. "Creating Interactive Landscapes with Multi-Method Modeling." In *81st SAA Meeting.* Orlando, Florida.
- Dell' Unto, N, G Landeschi, T Leander, A Touat, M Dellepiane, M Callieri, and D Ferdani. 2016. "Experiencing Ancient Buildings from a 3D GIS Perspective: A Case Drawn from the Swedish Pompeii Project." *Journal of Archaeological Method and Theory* 23 (1): 73–94.



- Diaz-Andreu, M., and T. Mattioli. 2015. "Archaeoacoustics of Rock Art: Quantitative Approaches to the Acoustics and Soundscape of Rock Art." In *Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*, 1049–58.
- Doyle, James A., Thomas G. Garrison, and Stephen D. Houston. 2012. "Watchful Realms: Integrating GIS Analysis and Political History in the Southern Maya Lowlands." *Antiquity* 86 (333): 792–807. doi:10.1017/S0003598X0004792X.
- Drucker, J. 2014. *Graphesis: Visual Forms of Knowledge Production*. Cambridge: Harvard University Press.
- E.N., Anderson, and Medina Tzuc F. 2005. *Animals and the Maya in Southeast Mexico*. Tucson: University of Arizona Press.
- Fahlander, Fredrik, and Anna Kjellström. 2010. *Making Sense of Things: Archaeologies of Sensory Perception. Stockholm Studies in Archaeology*. Vol. 53. file:///Users/jeltsjestobbe/Documents/SENTE VERSIES/LITERATUUR PROMOTIETIJD.sente6lib/Contents/Attachments/Fahlander/2010/Making sense of things. Archaeologies of sensory p/Fahlander 2010 Making sense of things. Archaeologi.pdf.
- Fash, B. 1992. "Late Classic Architectural Sculpture Themes in Copan." *Ancient Mesoamerica* 3: 89–104.
- Fash, W. 2001. *Scribes, Warriors, and Kings: The City of Copan and the Ancient Maya*. London: Thames and Hudson.
- Fash, W, and B Fash. 1996. "Building a World-View: Visual Communication in Classic Maya Architecture." *RES: Anthropology and Aesthetics* 29: 127–47.
- Feld, S, and K Basso. 1996. *Senses of Place*. Santa Fe: School of American Research Press.
- Feld, Steven. 1996. "Waterfalls of Song: An Acoustemology of Place Resounding in Bosavi, Papua New Guinea." In *Senses of Place*, 91–135.
- Fernández-Palacios, B, D Morabito, and F Remondino. n.d. "Access to Complex Reality-Based 3D Models Using Virtual Reality Solutions." *Journal of Cultural Heritage* 23: 40–48.
- Forte, M, and E Bonini. 2010. "Embodiment and Enaction: A Theoretical Overview for Cybercommunities." In *Heritage in the Digital Era*, 45–56. Essex: Multi-Science Publishing.
- Forte, M, and F Siliotti. 1997. *Virtual Archaeology*. London: Thames and Hudson.
- Forte, Maurizio. 2016. "Cyber Archaeology: 3D Sensing and Digital Embodiment." In *Digital Methods and Remote Sensing in Archaeology*, edited by Maurizio Forte and Stefano Campana, 271–89. Springer.
- Frischer, Bernard, and Anastasia Dakouri-Hild. 2008. "Beyond Illustration: 2d and 3d Digital Technologies as Tools for Discovery in Archaeology." *BAR International Series*.
- Garner, Tom A. 2018. *Echoes of Other Worlds: Sound in Virtual Reality*. Palgrave Macmillan. doi:10.1007/978-3-319-65708-0.
- Gillings, Mark. 1999. "Engaging Place: A Framework for the Integration and Realisation of Virtual-Reality Approaches in Archaeology." *BAR International Series* 750: 247–54.

- Goodwin, Graham, Heather Richards-Rissetto, Kristy E. Primeau, and David E. Witt. 2018. "Soundscapes and Visionscapes: Investigating Ancient Maya Cities with GIS and 3D Modeling." Presented at 83rd Annual Meeting of the Society for American Archaeology. Washington DC.
- Hall, E. 1966. *The Hidden Dimension*. Garden City: Anchor Books.
- Hall, E. 1968. "Proxemics." *Current Anthropology* 9: 83–108.
- Hamilakis, Y. 2013. *Archaeology and the Senses: Human Experience, Memory, and Affect*. New York: Cambridge University Press.
- Helmer, M, and D Chicoine. 2013. "Soundscapes and Community Organization in Ancient Peru: Plaza Architecture at the Early Horizon Center of Caylán." *Antiquity* 87 (335): 92–107.
- Hendon, J. 2012. "Neighborhoods in Pre-Hispanic Honduras." In *The Neighborhood as a Social and Spatial Unit in Mesoamerican Cities*, edited by M Arnaul, L Manzanilla, and Smith M. Tucson: University of Arizona Press.
- Hernandez, Anaya. 2006. "Strategic Location and Territorial Integrity: The Role of Subsidiary Sites in the Classic Maya Kingdoms of the Upper Usumacinta Region." *Internet Archaeology* 19.
- Houston, Stephen D, David Stuart, and Karl A Taube. 2006. *The Memory of Bones : Body, Being, and Experience among the Classic Maya. Joe R and Teresa Lozano Long Series in Latin American and Latino Art and Culture*. doi:10.1017/CBO9781107415324.004.
- Houston, Stephen, John Robertson, and David Stuart. 2001. "More on the Language of Classic Maya Inscriptions." *Current Anthropology* 42 (4): 558–59. doi:10.1086/322544.
- Howey, Meghan, and Marieka Brouwer-Burg. 2017. "Assessing the State of Archaeological GIS Research: Unbinding Analyses of Past Landscapes." *Journal of Archaeological Science* 84: 1–9.
- Hume, Lynne. 2007. *Portals: Opening Doorways to OTher Realities Through the Senses*. Oxford: Berg.
- Inomata, Takeshi. 2006. "Plazas, Performers, and Spectators: Political Theaters of the Classic Maya." *Current Anthropology* 47 (5): 805–42. doi:10.1086/506279.
- Isendahl, C, and M Smith. 2013. "Sustainable Agrarian Urbanism: The Low-Density Cities of the Mayas and Aztecs." *Cities* 31: 132–43.
- King, Stacie M., and Gonzalo Sánchez Santiago. 2011. "Soundscapes of the Everyday in Ancient Oaxaca, Mexico." *Archaeologies* 7 (2): 387–422. doi:10.1007/s11759-011-9171-y.
- Kitchin, Rob. 2014. *Data Revolution : Big Data, Open Data, Data Infrastructures and Their Consequences. Data Revolution*.
- Kittler, Friedrich. 2006. *Gramophone, Film, Typewriter*. Stanford: Stanford University Press.
- Kurjack, Edwards. 2003. "Palace and Society in the Northern Maya Lowlands." In *Maya Palaces and Elite Residences: An Interdisciplinary Approach*. Austin: University of Texas Press.
- Landau, Kristin. 2015. "Spatial Logic and Maya City Planning: The Case for Cosmology." *Cambridge Archaeological Journal*. doi:10.1017/S095977431400105X.

- Llobera, Marcos. 2011. "Archaeological Visualization: Towards an Archaeological Information Science (AISc)." *Journal of Archaeological Method and Theory*. doi:10.1007/s10816-010-9098-4.
- Llobera, Marcos. 2001. "Building Past Landscape Perception with GIS: Understanding Topographic Prominence." *Journal of Archaeological Science* 28 (9): 1005–14. doi:10.1006/jasc.2001.0720.
- Llobera, Marcos. 2007. "Reconstructing Visual Landscapes." *World Archaeology* 39 (1): 51–69. doi:10.1080/00438240601136496.
- Looper, Matthew G. 2009. *To Be Like Gods, Dance in Ancient Maya Civilization*. Ebook. doi:10.1017/CBO9781107415324.004.
- Lorig, R. 2016. "Noise Mapping: Modeling Chronic Natural Gas Compressor Noise across Pennsylvania State Forests in the Marcellus Shale Formation." [https://gis.education.psu.edu/sites/default/files/capstone/Lorig\\_596B\\_20160601.pdf](https://gis.education.psu.edu/sites/default/files/capstone/Lorig_596B_20160601.pdf).
- Low, Setha M., and Denise Denise Lawrence-Zuniga. 2003. "Anthropology of Space and Place: Locating Culture." *24 Yaca*, 436. doi:10.1111/j.1467-9655.2006.00289\_11.x.
- Lyons, M. 2016. "A 3D Reconstruction of Structure 10L-18 in Copán, Honduras: Data Structuring for Transparency." University of Bonn.
- McBride, Alexis. 2014. "The Acoustics of Archaeological Architecture in the Near Eastern Neolithic." *World Archaeology* 46 (3): 349–61. doi:10.1080/00438243.2014.909150.
- Mewan, Gordon. 2006. "Cultural Landscapes in the Ancient Andes: Archaeologies of Place." *American Anthropologist* 108 (4): 914–15. doi:10.1353/hir.2006.0025.
- Mewan, Gordon. 2006. "Cultural Landscapes in the Ancient Andes: Archaeologies of Place." *American Anthropologist* 108 (4): 914–15. doi:10.1353/hir.2006.0025.
- Millhauser, John K., and Christopher T. Morehart. 2016. "The Ambivalence of Maps: A Historical Perspective on Sensing and Representing Space in Mesoamerica." In *Digital Methods and Remote Sensing in Archaeology*, 247–68. doi:10.1007/978-3-319-40658-9\_11.
- Mills, S. 2014. *Auditory Archaeology: Understanding Sound and Hearing in the Past*. Walnut Creek: Left Coast Press.
- Mlekuz, D. 2004. "Listening to Landscapes: Modelling Past Soundscapes in GIS." *Internet Archaeology* 16.
- Mongelluzzo, R. 2013. "Maya Palaces as Experiences Ancient Maya Royal Architecture and Its Influence on Sensory Perception." In *Making Senses of the Past, Toward a Sensory Archaeology*. Carbondale and Edwardsville: Southern Illinois University Press.
- Moore, Jerry D. 1996. "The Archaeology of Plazas and the Proxemics of Ritual: Three Andean Traditions." *American Anthropologist* 98 (4): 789–802. doi:10.1525/aa.1996.98.4.02a00090.
- Moore, Jerry D. 1996. "The Archaeology of Plazas and the Proxemics of Ritual: Three Andean Traditions." *American Anthropologist* 98 (4): 789–802. doi:10.1525/aa.1996.98.4.02a00090.
- Newsome, E. 2001. *Trees of Paradise and Pillars of the World: The Serial Stelae Cycle "18-Rabbit-God K," King of Copan*. Austin: University of Texas Press.

- Paliou, E. 2014. "Visibility Analysis in 3D Built Spaces: A New Dimension to the Understanding of Social Space." In *Spatial Analysis and Social Spaces: Interdisciplinary Approaches to the Interpretation of Prehistoric and Historic Built Environments*, edited by E Paliou, U Lieberwirth, and S Polla. Berlin, Boston: De Gruyter.
- Parmington, Alexander. 2011. *Space and Sculpture in the Classic Maya City*. *Space and Sculpture in the Classic Maya City*. doi:10.1017/CBO9780511976704.
- Primeau, Kristy E., and David E. Witt. 2017. "Soundscapes in the Past: Investigating Sound at the Landscape Level." *Journal of Archaeological Science: Reports*. doi:10.1016/j.jasrep.2017.05.044.
- Prufer, Keith M., Amy E. Thompson, and Douglas J. Kennett. 2015. "Evaluating Airborne LiDAR for Detecting Settlements and Modified Landscapes in Disturbed Tropical Environments at Uxbenká, Belize." *Journal of Archaeological Science* 57: 1–13. doi:10.1016/j.jas.2015.02.013.
- Rainbird, P. 2010. "The Body and the Senses: Implications for Landscape Archaeology." In *Handbook of Landscape Archaeology*, 263–71. Walnut Creek: Left Coast Press.
- Rainbird, P. 2010. "The Body and the Senses: Implications for Landscape Archaeology." In *Handbook of Landscape Archaeology*, edited by W.A. Congress and B.D. Thomas, 263–71. Walnut Creek: Left Coast Press.
- Rainio, Riitta, Antti Lahelma, Tiina Äikäs, Kai Lassfolk, and Jari Okkonen. 2017. "Acoustic Measurements and Digital Image Processing Suggest a Link Between Sound Rituals and Sacred Sites in Northern Finland." *Journal of Archaeological Method and Theory*. doi:10.1007/s10816-017-9343-1.
- Ramsay, Stephen. 2011. *Reading Machines: Toward an Algorithmic Criticism*. *Topics in the Digital Humanities*. doi:10.1093/llc/fqs042.
- Reed, Sarah E., Jennifer L. Boggs, and Jacob P. Mann. 2012. "A GIS Tool for Modeling Anthropogenic Noise Propagation in Natural Ecosystems." *Environmental Modelling and Software* 37: 1–5. doi:10.1016/j.envsoft.2012.04.012.
- Richards-Rissetto, H. 2010. "Exploring Social Interaction at the Ancient Maya City of Copán, Honduras: A Multi-Scalar Geographic Information Systems (GIS) Analysis of Access and Visibility." University of New Mexico.
- Richards-Rissetto, Heather. 2017. "An Iterative 3D GIS Analysis of the Role of Visibility in Ancient Maya Landscapes: A Case Study from Copan, Honduras." *Digital Scholarship in the Humanities* 32: ii195-ii212. doi:10.1093/llc/fqx014.
- Richards-Rissetto, Heather. 2013. "From Mounds to Maps to Models: Visualizing Ancient Architecture across Landscapes." In *Proceedings of the DigitalHeritage 2013 - Federating the 19th Int'l VSMM, 10th Eurographics GCH, and 2nd UNESCO Memory of the World Conferences, Plus Special Sessions fromCAA, Arqueologica 2.0 et Al.*, 2:519–22. doi:10.1109/DigitalHeritage.2013.6744820.
- Richards-Rissetto, Heather, and Kristin Landau. 2014. "Movement as a Means of Social (Re)production: Using GIS to Measure Social Integration across Urban Landscapes." *Journal of Archaeological Science* 41: 365–75. doi:10.1016/j.jas.2013.08.006.
- Sanchez, Julia L. J. 2007. "Procession and Performance: Recreating Ritual Soundscapes among the Ancient Maya." *The World of Music* 49 (2): 35–44. <http://www.jstor.org/stable/41699763> <http://about.jstor.org/terms>.
- Schele, Linda, and Mary E. Miller. 1986. "The Blood of Kings: Dynasty and Ritual in Maya Art - Introduction." In *The Blood of Kings: Dynasty and Ritual in Maya Art*.

- Sharer, R, and L Traxler. 2006. *The Maya Sixth Edition*. Stanford: Stanford University Press.
- Sharpe, Ashley E. 2015. "A Reexamination of the Birds in the Central Mexican Codices." *Ancient Mesoamerica*. doi:10.1017/S0956536114000297.
- Stockli. 2007. "Playing Music as Domestic Activity? Interpretations of the Finds of Sound-Producing Artifacts at Aguateca, El Peten, Guatemala." *The World of Music* 49 (2): 17–33.
- Sullivan, Elaine A. 2017. "Seeking a Better View: Using 3D to Investigate Visibility in Historic Landscapes." *Journal of Archaeological Method and Theory* 24 (4): 1227–55. doi:10.1007/s10816-016-9311-1.
- Tilley, C. 1994. *A Phenomenology of Landscape*. Oxford: Berg Publishers.
- Tilley, Christopher. 1994. "A Phenomenology of Landscape: Places, Paths and Monuments." *Journal of Social Archaeology*, [xi], 221 . doi:10.1017/CBO9781107415324.004.
- Schwerin, J von. 2004. "On Reconstructing and Performing Maya Architecture: Structure 10L-22, Copan Honduras (AS715)." Columbia University.
- Schwerin, Jennifer Von. 2011. "The Sacred Mountain in Social Context. Symbolism and History in Maya Architecture: Temple 22 at Copan, Honduras." *Ancient Mesoamerica* 22 (2): 271–300. doi:10.1017/S0956536111000319.
- White, Devin, and Sarah Surface-Evans. 2012. *Least Cost Analysis of Social Landscapes: Archaeological Case Studies*. University of Utah Press.