Combining 3D Visibility Analysis and Virtual Acoustics Analysis for the Architectural Study of Ancient Theatres

Maria Cristina Manzetti

Abstract The research presented in this chapter demonstrates the fruitful combination of interdisciplinary and multisensory approaches in the field of archaeology. Several disciplines, such as architecture, archaeology, computer science, acoustics and geophysics, cooperated to obtain new data and to elaborate new hypotheses about the original structure of the Roman theatres in Crete. All the information available about these monuments (such as ancient drawings, descriptions of travellers, plans, archaeological reports, aerial pictures and geophysical anomalies) were the basis to hypothesise their original architecture, together with the support of comparisons with well-preserved Roman theatres and with Vitruvius' proportions. These reconstructive hypotheses were visualised by 3D models and their accuracy was verified through a new methodology that sees the application of 3D visibility analysis and virtual acoustics analysis. The 3D visibility analysis was useful to verify the level of visibility of the stage by the spectators in the seating area. The virtual acoustics analysis was used to obtain quantitative values of acoustic parameters helpful to judge the acoustic quality of the 3D reconstructions. The auralisation was also carried out to attain a subjective parameter about acoustic perception. In particular, by 3D visibility analysis and virtual acoustics analysis, it is possible to verify the reliability and the accuracy of hypothetical reconstructions, assuming that every spectator was able to watch the stage and able to listen and to comprehend any performance. The case study presented here is the theatre at the acropolis of Gortyna. Two different 3D reconstructions were tested and it has resulted that the 3D model of the theatre which maintains some Greek characteristics is the most reliable one. This approach made it possible to obtain data that could not be obtained otherwise, as well as raising new questions and opening up new perspectives.

Keywords Roman theatres · 3D visibility analysis · Virtual acoustics analysis · Gortyna

M. C. Manzetti (✉)
Department of History and Archaeology, University of Cyprus, Nicosia, Cyprus
e-mail: cristinamanzetti@gmail.com; manzetti.maria-cristina@ucy.ac.cy

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1 Introduction

The sector of Cultural Heritage has always been characterised by collaboration among several disciplines. We cannot achieve a thorough study of a monument if we do not consider its historical context, its architecture and its graphical representation. Besides, we cannot completely understand an archaeological site if we do not take into account its geographical context, history, geology, artefacts and social and religious functions. History, architecture, history of art, geography, sociology, anthropology and theology are only some of the disciplines that together contribute to a better and deeper knowledge of what we now consider symbols of the past, representing our culture.

In the last three decades, a new bailiwick has been involved in the field of Cultural Heritage: information technology (IT) and virtual reality. Virtual analyses, 3D modelling, virtual reality and digital media are some of the very useful instruments borrowed from the technological sector and applied to the field of Cultural Heritage, above all to archaeology. This research project exploits these recently developed tools and proposes an interdisciplinary approach that sees the cooperation and the integration of archaeology, architecture, 3D modelling, virtual analyses and acoustics. New and peculiar disciplines can take shape through interdisciplinarity. An example of a new field born from the combination of archaeology and information technology is Virtual Archaeology. The expression ‘Virtual Archaeology’ was coined by Reilly (1991) and since then its success has increased until it has been recently chosen to give the name to a biennial international forum organised by the State Hermitage Museum of Saint Petersburg (http://www.virtualarchaeology.ru/). With the expression virtual reality, Reilly explains that archaeologists can virtually reproduce an archaeological excavation through 3D modelling, and thus visualise and analyse the excavated area over and over again, without losing the possibility to verify the excavated layers once they have been removed. Many steps have been made since then but there is still a long way to go; for example, developing a more systematic application of interdisciplinary approaches in archaeology.

The fundamental contribution of interdisciplinarity, rather than multidisciplinarity, in the archaeological sector, is also expressed by the Principles of Seville, which are the eight international principles of Virtual Archaeology. The first principle is ‘interdisciplinarity’, and it states that the cooperation of a professional team with backgrounds in different sciences is necessary and, most importantly, that experts need to exchange their ideas rather than working independently (Lopez-Menchero Bendicho 2013).

The workflow that I am going to present in this chapter is the result of an interdisciplinary approach applied to the study and the valorisation of the Roman theatres in Crete. This innovative methodology combines archaeology, architecture, acoustics and computer science. The methodology developed takes into account several disciplines and focuses on two human senses: sight and hearing. The main aim of this chapter is to demonstrate the fruitful results that archaeologists can achieve by implementing an interdisciplinary and multisensory approach.

Senses have only recently become part of archaeological investigation, with senses beyond sight being recognised as instruments that can enhance our knowledge of the past cultures (Betts 2017; Day 2013; Hamilakis 2011). Visibility has been examined extensively in archaeology since the 1980s and a good review is presented by Lake and Woodman who explain the two main groups in this field: non-GIS visibility studies and GIS visibility studies (Lake and Woodman 2003). Visibility studies are generally considered useful to investigate the distribution of sites and relationships among them (Wheatley 1995), to understand the defensive techniques of ancient populations (Loots et al. 1999), to study the likely rituals connected to prehistoric monuments (Fisher et al. 1997; Wheatley 1995) and to examine the connection between monuments/sites and astronomical events (Ruggles et al. 1993).

Sight has often been considered by archaeologists the main sense of human beings useful to investigate archaeological sites but, more recently, some scholars (Hamilakis 2013; Wheatley 2014) observed the bias for this approach and the consequent inaccuracy in the results and interpretations.

While sight has largely been privileged in archaeology, 'archaeoacoustics' (Scarre and Lawson 2006) is an emerging sub-field, often having a focus on the role and behaviour of sound within prehistoric sites (Devereux 2001), mainly in order to deduce the rituality connected to those spaces.

One of the first case studies in which a combined approach was applied is the sixth-century Byzantine church of San Vitale in Ravenna (Italy) (Paliou and Knight 2013). This study combined visibility and acoustics analyses, intending to obtain more information about the sensations the worshippers were feeling and the stimuli they were receiving within the church during the liturgy. Paliou and Knight created a combined map (visual data obtained by visibility analysis plus acoustics data derived from the in situ measurements) representing the sensory catchment[1] inside the church, to deduce which were the privileged positions in the building to assist the liturgy. In particular, they wanted to examine the social differences between men and women, according to the area they occupied within the church (floor and *matroneum*). In this case, the combination of visibility and acoustics analyses allowed a meaningful and valuable conclusion to be reached about which social discriminations were determined by the church's architecture.

This chapter applies a similar methodology in order to verify possible architectural reconstructions of the Roman theatres of Crete. The acoustics analysis in this research also helped to formulate hypotheses about the kind of performance that was represented in those spaces.

In particular, the research question is: how can we obtain more information about the architecture of monuments that nowadays are destroyed? Can new technologies be a fruitful instrument to improve the knowledge of what is left of a glorious past? and, since the subject of my research are ancient buildings for entertainment (where people

[1] Paliou and Knight were inspired by Frieman and Gillings definition of 'sensory envelop' to carry out their research. According to the authors, a sensory envelop identifies 'an area where all the senses are engaged' (Frieman and Gillings 2007).

used to go mainly[2] to watch and to listen to a performance) 'can the examination of the sensorial aspect help in the reconstruction of the architecture and the history of those monuments?'.

This chapter aims to investigate the potentialities of an interdisciplinary and multisensory approach in archaeology. In particular, the proposed methodology and workflow will demonstrate its effectiveness for obtaining information about the architecture of ancient theatres and for raising new questions.

The study required several steps to be completed. First, all the documents about the Roman theatres of Crete were collected and examined. Then, several 3D models for each chosen theatre were realised according to reconstructive hypotheses based on the combination of available data, comparisons with well-known Roman theatres and Vitruvian rules. These 3D models were used to inspect the visibility of the stage from the cavea and the quality of sound in the seating area.

2 The Roman Theatres in Crete

There are 12 known Roman theatres in Crete, located around the island. In the prefecture of Chania (west side of the island), there were four: the one in Chania and the one in Kissamos are now respectively destroyed and under the modern village, the one in Aptera is well known and still visible in the archaeological site, and the one in Lissos is in the archaeological area but excavations have started only very recently. In the prefecture of Heraklion (central-east part of the island), there were five: three of them are located in the ancient Roman capital of Crete, in Gortyna, one is in Chersonissos, one is supposed to be in Lyttos but it has not been identified yet. In the prefecture of Lassithi (the eastern part of the island), there were three: two of them are located within the town of Ierapetra, and one is on the little island of Koufonissi. It is still uncertain if there was another theatre in Tsousouros (south Heraklion).

For a long time, the Roman theatres in Crete have been neglected, while a large part of attention was addressed towards the rich Minoan past of the island. This initial attitude of the archaeologists might surprise considering that the relevance of several Roman remains (including theatres) was already witnessed at the end of the sixteenth century. Italian (Beschi 1999), British (Pashley 1837; Pococke 1745; Spratt 1865) and French (Pitton de Tournefort 1717) travellers documented the presence, and sometimes also the aspect, of some of these monuments. At the very end of the nineteenth century-beginning of the twentieth century, some archaeological investigations, conducted by the Italian Mission of Archaeology in Crete, started, above all in Gortyna, always considered the most interesting Roman site of the island because it was the capital of the Roman province of Crete and Cyrenaica since 67 AD (Scuola Archeologica Italiana di Atene 1984). Lately, since the beginning of the nineteenth century, systematic archaeological excavations have begun at the site occupied by

[2] Ancient theatres could be also used as spaces for meetings, ritual ceremonies and as a seat of congregations.

some of the theatres. They allowed to achieve very good results in the understanding of the history and the structure of some of these ancient buildings, as in the case of the theatre of Aptera (Vana Niniou-Kindeli and Chatzidakis 2016), which excavations are carried out by the 23rd Ephorate of Prehistoric and Classical Antiquities of Greece, and in the case of the theatre of the *Pythion* in Gortyna (Bonetto et al. 2019; Bonetto and Francisci 2014) which excavations are conducted by the University of Padua and the Italian School of Archaeology at Athens. Summarising, the Roman theatres in Crete are not very well known, are not very well preserved and only a few of them have been investigated by accurate archaeological excavations. Despite the evident difficulties in trying to extrapolate information from such kind of scenario, these monuments definitely deserve to be examined to restore their honour and to avoid them to be completely forgotten. It is unnecessary to say that archaeological excavations are the main instrument that would allow specialists to have a better understanding of the structure and the history of these theatres, but there are some particular circumstances where archaeological excavations are not enough. Often, as in the case of the Roman theatres in Crete, the ancient buildings are not fully preserved and it is not always easy to deduce their original aspect from the collapsed remains since they could have been pillaged or destroyed. In these cases, the new technologies can be of great help because we can virtually reconstruct such buildings according to our hypotheses and verify their accuracy or validity through 3D visualisation and virtual analyses. In this specific case study, 3D visibility analysis and virtual acoustics analysis have been considered to be, at the moment, the most meaningful ones to apply in order to enhance the knowledge about the architecture and the function of the theatres. The idea to implement this typology of analyses derived from the main function of the theatre itself: it is made to watch and to listen to a performance. The Greek word θέατρον (theatre) comes from the ancient Greek verb θεάομαι which means ‘to see, to watch’ (Pappalardo 2007), while the Romans used to call it *auditorium*, from the Latin verb *audio*, that is ‘to listen’ (Bieber 1981). These observations lead to assume that the spectators were able to see what was happening on the stage and to follow the movements of the actor/s and that they were able to understand the words of the performer/s or to enjoy the music. Consequently, the structure of the theatres needed (and still needs) to respect these prerequisites, that is to allow the visibility of the stage from the seating area and the good perception of the sound (both music or talk). The observance of these requisites in the reconstructive hypotheses of the Roman theatres in Crete have been verified through 3D visibility analysis and virtual acoustics analysis.

3 Methodology

Before I go into detail about the innovative tools (3D visibility analysis and virtual acoustics analysis) used during this study, I want to underline that the traditional approach has been implemented too. The research started with the collection and the analysis of all available data: archaeological reports, images, aerial pictures, ancient plans, descriptions of travellers, surveys and results of geophysical prospection. The combined study of all these documents (Manzetti et al. 2015) enabled to formulate the first hypothesis about the structure of each theatre. If there was not enough information to reconstruct their height, comparisons with well-preserved theatres (as Aspedos and Orange) and the Vitruvian's rules described in '*De Architectura*' (Morgan 1914) were considered. AutoCad and 3D Studio Max were used to draw the plan of the theatres and to extrude it to create 3D models of the reconstructive hypotheses of the monuments. Since these are only hypotheses, each theatre has been represented in more than one 3D model with some possible variations in its structure. All 3D models of each theatre were analysed through 3D visibility and virtual acoustics in order to verify which hypothesis is the most reliable one and if they are accurate reconstructions.

3.1 3D Visibility Analysis

As it has been already mentioned, the visibility analysis in archaeology has been widespread for more than thirty years. Many things changed since then and more quantitative and accurate methods have been developed. One of the main issues about visibility analysis has always been the bi-dimensional approach since we live in a three-dimensional world (Bishop et al. 2000; Paliou et al. 2011). As Tufte reminds us, studying 'flatlands' (maps, drawings and pictures) is not the solution, we have to reproduce objects as they are if we want to understand them (Tufte 1990). Finally, a method for visibility analysis in a fully 3D environment was conceived a few years ago and one of the very first examples is the study of visibility within the *Insula* V 1 of Pompeii, under the Swedish Pompeii Project (Landeschi et al. 2016).

The 3D visibility analysis can be performed through ArcScene which allows creating lines of sight between the observer and the target in a 3D environment, thus it considers the height of the buildings and any other obstacle in the field of view.

Once the 3D models of the Roman theatres of Crete have been realised, a grid of points (representing the observers) has been placed in the seating area. Each grid is composed of four lines dislocated in the cavea (two lines are placed next to the side retaining walls and the other two are toward the centre) with a point over each row of seats.[3] Each point is located 75 cm above the seat, to simulate the average height of a seated person. A target line (representing the actor/s) was placed approximately at the centre of the stage, 160 cm above the floor to simulate the average height of a standing person. The 3D models, the grid of points and the lines were imported into ArcScene where the lines of sight were constructed. The lines of sight are composed of lines of two colours that are built between all the observer points and the target. The green lines represent the visible trajectories, that means the observer points from which the green lines originate can see the area of the target that the lines hit. The red lines are the not visible trajectories, so the observers cannot see

[3] The number of points varies according to the number of rows of seats of the cavea of each theatre.

the target or part of it. The visualisation of the lines of sight in a 3D environment allows us to understand from which area of the building the green and red lines originated and which part of the target is more or less visible. It is also possible to visualise the obstruction points derived from the construction of the lines of sight. The obstruction points are marking the exact location where the lines of sight hit an object that impedes the visibility. In the case of the theatres, this tool is useful to verify that some architectural structures have not been reproduced in an uncorrected position and/or size (for instance: retaining walls too high, stage too high, *basilicae* too close to the cavea).

Besides, another analysis is possible through ArcScene which is called 'visibility', similar to viewshed analysis. The implementation of this tool produces a visual map of frequencies, which is a 2D file but during the calculations, it takes into account the three-dimensional aspect of the objects. Several colours on the map represent the different levels of visibility: each colour corresponds to a specific number of spectators, thus it is possible to understand how many spectators see a specific area of the theatre. In our case, we are interested to know how many spectators can see the stage or part of it.

3.2 Virtual Acoustics Analysis

Already since the sixth century BC, sound (its generation, its behaviour and its effects) was investigated by ancient Greeks. Pythagoras was interested in the pitch of sounds. He conducted some experiments and he finally conceived the Pythagorean tuning, that means the attribution of a series of numbers to the notes according to their pitch. Aristotle (*De Anima*) as well examined sound, its propagation and its creation by the man. Thus, already in fourth century BC, Greeks knew that an auditory body, a knock and the air were the necessary elements to generate a sound, as it was already mentioned by Plato (*Timeo*). These studies, along with the one by Aristoxenus[4] (*Aristoxenou Armonika Stoicheia*), demonstrate that ancient Greeks had quite extensive knowledge about sound and acoustics. They were applying their precious awareness for the construction of buildings where the sound was a fundamental element, as demonstrated by Plutarch (*Moralia*). He narrates that the architect of the theatre of Pella dissuaded Alexander the Great to build a *proscaenium* made out of bronze because such material would have negatively influenced the acoustics of the space.

During the centuries, the knowledge about acoustics increased: the Romans were able to give a more specific description of the effects of the sound. In our case, it is useful to take as an example the architect Vitruvius who, while he was suggesting a proper place where to build a theatre, described different possible sounds, which one to avoid and which one to pursue. He depicts four distinct spaces that influence the behaviour of the sound and therefore its perception. A *desonans* space is where the first sound obstacles the second; a *circumsonans* space is where it is not possible

[4] He studied the perception of the sound.

to discern the different meanings of the sound; the *resonans* space is where echo is generated; a *consonans* space is where the words are distinct and clear in tone. Vitruvius recommends looking for a *consonans* space to build a theatre that can satisfy the need of the spectators to understand the performances.

This brief excursus of ancient literature about sound is useful to understand the utility of analysing the acoustics of ancient theatres. It shows the importance that acoustics had already in the past and therefore nowadays it can give meaningful signs, helpful to interpret ancient architectures. The precious contribution that the study of acoustics in ancient theatres can bring is so evident that in the last 50 years some scholars already systematically investigated this aspect. François Canac carried a detailed and thorough study about the acoustics of ancient theatres, taking measurements in situ (in France, Italy and Asia Minor) and also simulated measurements in scaled models (Canac 1967). He managed to identify the acoustics role of architectural elements such as niches, corridors, roof, walls, seats and orchestra's floor. Only short and sporadic studies were conducted since then, mainly on the well-preserved theatres. A large project on the 'Identification, Evaluation and Revival of the Acoustical Heritage of Ancient Theatres and Odea', ERATO, came out only in 2003–2006. It allowed the discovery of numerous acoustics characteristics of ancient theatres such as Aspendos (Turkey), Aphrodisia (Turkey), Jerash (Jordan) and Syracuse (Italy) (Erdogan 2006). During the ERATO project, in situ measurements were not the only data collected. The software Odeon Room Acoustics was also used to virtually analyse some of the theatres and to compare the real measurements with the simulated ones. The application and the results of virtual acoustics analysis have been presented during the conference Acoustics of Ancient Theatres at Patras in 2011 as well (Foteinou and Murphy 2011; Iannace et al. 2011a, b; Lokki et al. 2011). These previous studies are very useful to this research since they allow to compare methods and results, and consequently to achieve a more accurate outcome.

The software Odeon Room Acoustics was used to analyse the Roman theatres of Crete as well as to facilitate the comparisons with the previous publications. The simplified versions of the 3D models of the theatres were imported into Odeon Room Acoustics. A grid of receivers was placed in the cavea (75 cm above the seats) corresponding to the spectators, and an omnidirectional source was approximately placed at the centre of the stage (160 cm above the floor) corresponding to the actor. The overall gain of the source was set at 60 dB that is equivalent to the human voice. In this research, the value of the sound corresponding to the human voice only has been considered because the theatres in Roman times were principally used for plays rather than musical performances.[5] Before starting with the analysis, it is necessary to adjust the main settings to obtain reliable results, according to the characteristics of the object, as it is suggested by the software handbook (Christensen and Koutsouris 2015). One of the main aspects to consider is that the Roman theatres are open-air

[5] The geometrical evolution of the theatre, from Greek to Roman times, (and of the theatrical texts as well) testifies indeed the passage from a performance with dancers and a chorus (which used to take place in the orchestra that from a circle becomes a semicircle) to a performance where the main character was the actor (located on the stage which became deeper and less high) (Bieber 1981).

theatres, they did not have any roof, not like in modern theatres, or ancient *odéia*, and to do fundamental calculations, like the reverberation time, it is indispensable to have a volume.[6] Therefore, it is necessary to build a bounding-box that 'seals' each theatre and to give each one of its surfaces a total absorption so that the sound rays would pass through them and the open-air characteristic is preserved. The other important step to take before starting the calculations is to assign the correct material to each surface of the 3D model.[7] We need to know which part of the theatre was made out of stone, wood, bricks, marble, etc. Odeon Room Acoustics offers a rich library of materials along with their absorption coefficients for each frequency. Once the calculations are done, we obtain results from many acoustic parameters that indicate different characteristics of the sound; to have a good quality of acoustics, the values of such parameters should fall into a specific range and the verification of these values enables to judge the acoustics of a room. The parameters that have been considered in this research are five: reverberation time, early decay time, clarity, definition, speech transmission index (for more acoustic parameters used for archaeological investigations, see also the research about the soundscape of the streets in Ostia (Veitch 2017)). The reverberation time and the early decay time are parameters related to the reverberation of sound.[8] More precisely, the reverberation time (RT) is the time a sound takes to decrease by 60 dB after it stops. For speech, the ideal time of reverberation is around 1 s, for music is around 2 s (Spagnolo 2014). If the reverberation time lengthens, it gives origin to the phenomenon of the echo. While the reverberation time is an objective value (it represents the real reverberation), the early decay time represents the subjective perception of the reverberation time, that means the feeling of how much the first reflections annoy the listener. It corresponds to the first 10 dB of decay and ideally should be the same as the reverberation time, but it is usually a little lower and the level of disparity between them is a signal of good or bad diffusion of the sound. Previous research dedicated to open-air and well-preserved theatres (Aspendos, Epidaurus, Jerash) demonstrated that in such spaces the difference between RT and EDT is between 0.2 and 0.4 s (Gade and Angelakis

[6] The reverberation time is equal to volume divided by the sum of the absorption coefficients of all the materials.

[7] Each material has a different absorption coefficient which influences the quality of the sound (see note 6).

[8] It is important to underline that sound is generally characterised by three components: direct sound, early reflections and late reflections. The direct sound is the part that directly reaches the ears of a listener, travelling in a straight line from the source, and it arrives before the other components. The early reflections come from sound hitting obstacles (such as walls, ceiling, floor, etc.) that reflect the received acoustic impulse; these are the first reflections that arrive after the direct sound. They cannot be distinguished by the ears but if they arrive within 20 ms after the direct sound, they improve the subjective intensity of the sound. The late reflections arrive after the early reflections: they contribute having the pleasant perception of the vastness of a room and enjoying a full experience of sound but, when reflections keep arriving for a long time, we have a reverberant sound that invalidates its comprehension. This happens because a long/repeated time of reflections makes a sound longer than it should be and when a second sound (that, for instance, can be the second syllable of a word) is emitted, the first sound is still audible, so that the two sounds are not identifiable and distinguishable, therefore they are not comprehensible.

2006). Clarity and definition are parameters connected to energetic criteria. Clarity (C80) represents the comprehension of a single sound within a complex signal. It consists of the ratio between the energy that arrives within 80 ms (that is the energy of the direct sound plus the energy of the early reflections) to the energy that arrives later. If the energy of the late reflections is higher than the energy of direct sound and early reflections, clarity (that is comprehension) is not very good. We may have appropriate acoustics for speech when the value of C80 is equal or greater than 3 dB, while, for a good listening of the music, we should need values under 3 dB (Spagnolo 2014). Definition (D50) indicates the level of clarity of the speech, the ease for the listener to understand the message of the speaker. The index of D50 is the ratio between the energy that arrives within the first 50 ms (direct sound plus early reflections) and the remaining energy of the signal. Also, in this case, the first energy has to be superior to the late energy to have an acceptable quality of the acoustics for the speech. The desirable value of D50 for speech is higher than 0.50, for music lower than 0.50 (by definition is included within 0 and 1) (Spagnolo 2014). The Speech Transmission Index (STI) is related to spoken intelligibility. It establishes objectively the quality of spoken, calculating the combined effect of background noise and reverberation on the intelligibility of the speech. When there are no interferences in the characteristics of modulation of the signal, there are suitable conditions of intelligibility. Values of STI between 0.60 and 0.75 are good; greater than 0.75 are excellent (Spagnolo 2014).

Summarising, through virtual acoustics analysis, we achieve quantitative results which contribute to adopting an objective and scientific approach that can be easily compared with similar studies and that allows judging the acoustics quality of a space. However, since we are in the field of senses, we have to consider also the subjective perception. Senses are always related to emotions, memories and cultures (Hamilakis 2013). The way we perceive sounds, landscapes, smells and materials is strictly connected to our previous experiences and also to our capabilities and sensibility. This is the reason why it is also important to consider the auralisation, which is the convolution between an anechoic file and the impulse response. Odeon Room Acoustics enable us to do the auralisation, producing audio files that sound how they would have sounded if they were directly recorded in situ. This process enables to listen to the reproduction of ancient performances as if we were physically in the space corresponding to the 3D model where the auralisation has been performed and therefore to live a subjective experience of the sound (Manzetti 2018a). To obtain some auralised files from the 3D models of the Roman theatres of Crete, an anechoic file, representing a monologue from the 'Trojan Women' by Euripides, was recorded at the Laboratory Of Sensors and Acoustics Orso Mario Corbino of the CNR in Rome thanks to Dr Calicchia, Dr Pace and Martina Giovanetti.

4 Case Study and Results

The most ancient theatre of Gortyna (the ancient capital of the Roman province of Crete and Cyrenaica) is placed on the south-east slopes of the acropolis of the ancient town. It is known as a Roman theatre but it has been originally built during the Greek times and was modified by the Romans at a later time. This probably explains the structure of the theatre, which is half-dug in the ground and half-built, as it was typical in Greek times. The theatre is currently under investigation by the Ephorate of Prehistoric and Classical Antiquities of Heraklion; archaeological excavations have started in 2011 (Kanta et al. 2014). The information about the theatre is quite numerous: an ancient drawing (Beschi 1999) and its old reinterpretation (Falkener 1854), descriptions by a British traveller (Spratt 1865), plan and section of the cavea by an early archaeologist of the Italian Mission of Archaeology in Crete (Taramelli 1902), recent studies (Barresi 2004), geophysical prospection (Sarris and Papadopoulos 2010) satellite images and recent archaeological excavations. However, unfortunately, this information is fragmentary and still does not clarify the original structure of the Roman theatre at the acropolis of Gortyna. In this case, 3D visibility analysis, virtual acoustics analysis and auralisation can contribute to shed light on the architecture of the theatre or to formulate new questions and raise problems that would not be evident without such kind of analyses.

Through the combination of all the above-mentioned information, also taking into account the Vitruvian's proportions and analogies with well-preserved Roman theatres, two hypothetical reconstructions of the theatre of the acropolis of Gortyna have been attempted. The difference between the two reconstructions is the presence of *parodoi* (the side entrances to the theatre) in the first one, determining a distance between seating area and scene building[9] (model N.1), and the presence of *basilicae* (rooms that flank the stage) connected to the cavea in the second one, which create an enclosed space,[10] together with a portico in *summa* cavea (model N.2).

To verify the visibility from the cavea to the stage, 120 observer points were placed in the seating area (Figs. 1 and 2) and lines of sight were constructed between this grid of observer points and the target line on the stage (Figs. 3 and 4). As it is expected, in both models, the non-visible trajectories are between the observer points located at the sides of the seating area and the extremities of the target line. The central part of the target line, which corresponds to the central part of the stage, is connected through visible trajectories to all the observer points, in both models.

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[9] The presence of *parodoi* was typical in Greek theatres. This hypothesis, here, is justified by the apparent absence of traces of structures between the seating area and the scene building. Barresi testifies the presence of vaulted blocks in that area that were probably necessary to cover the *parodoi* (Barresi 2004), but no *tribunalia* are documented that would have connected the cavea and the scene building. Moreover, as it was mentioned before, the theatre at the acropolis of Gortyna was originally built in Greek time and it might be possible that some of its characteristics have been preserved during the Roman modifications.

[10] This kind of structure is typical of the Roman theatres and it has also been proposed by the archaeologists who excavate the theatre at the conference Ergo Kritis in November 2016 in Rethymno, Greece.

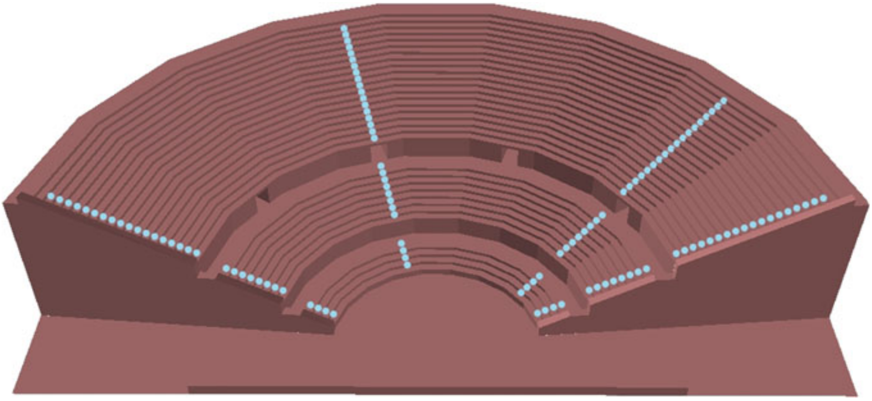

Fig. 1 Model N.1 together with the observer points

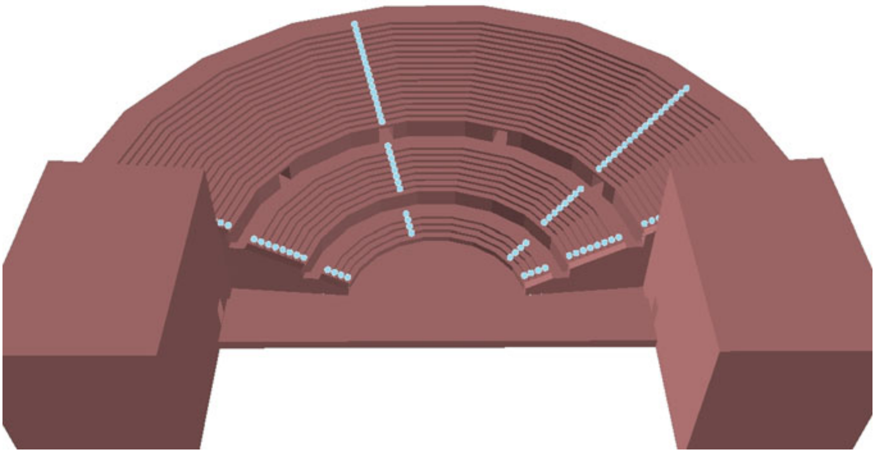

Fig. 2 Model N.2 together with the observer points

More exactly, if we calculate the percentage of visible and non-visible trajectories for both models, we see that the difference between the two hypothetical reconstructions is negligible the model N.1 presents the 17% of non-visible trajectories, model N.2 the 18%. However, differences are more noticeable in the 'maps of frequency of visibility'. From the frequency of visibility map of model N.1, it is clear that the central part of the stage is completely visible to all 120 observer points (Fig. 5). While, the map of frequency of visibility of model N.2 shows that the visible area of the stage, to all observer points, is only the very frontal part of it (Fig. 6). The centre and the back of the stage is still visible to a high number of 'spectators' but no to all of them (between 95 and 115).

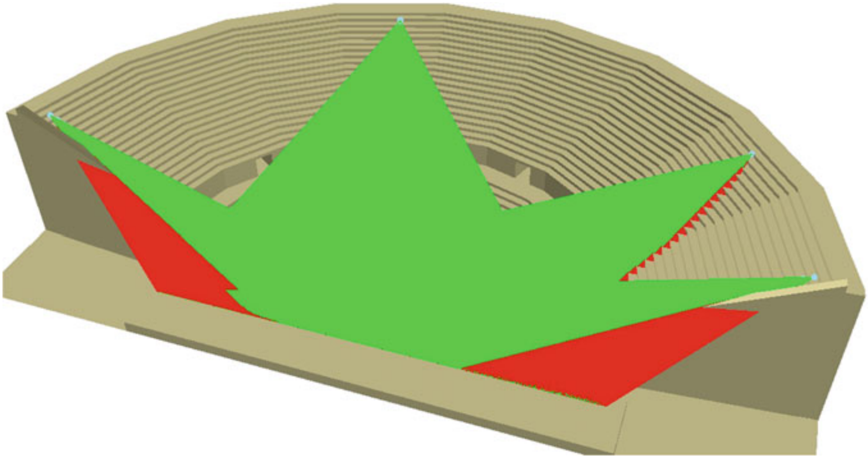

Fig. 3 Lines of sights built from the observer points in the seating area and the target line on the stage (model N.1). The green lines correspond to visible trajectories and the red lines correspond to non-visible trajectories

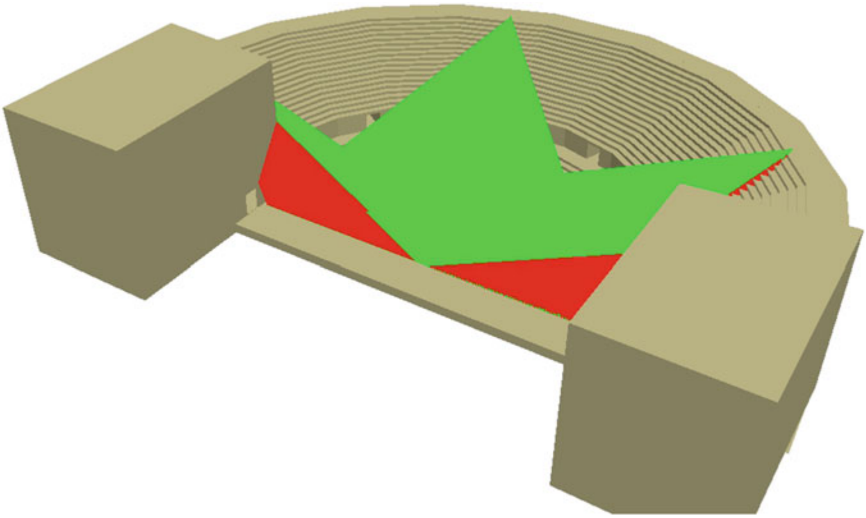

Fig. 4 Lines of sights built from the observer points in the seating area and the target line on the stage (model N.2). The green lines correspond to visible trajectories and the red lines correspond to non-visible trajectories

The same 3D models were examined through the virtual acoustics analysis as well, with 30 receivers placed in the seating area (Fig. 7). For each receiver, the obtained values of RT, EDT, C80, D50 and STI, at the range of frequencies 125–2000 Hz, were considered. Tables 1 and 2 show the average values of all 30 receivers

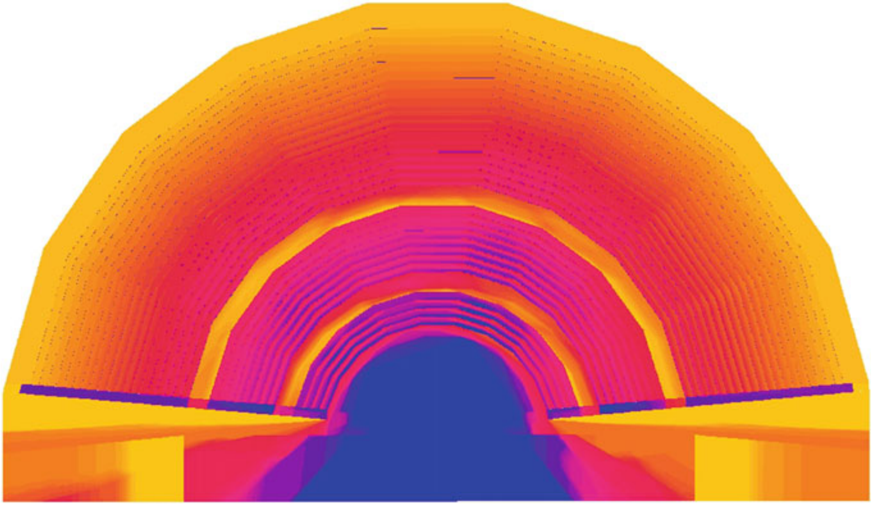

Fig. 5 Map of frequency of visibility of the theatre at the acropolis of Gortyna (model N.1). The blue colour indicates the areas that are visible by all observer points and the yellow colour indicates the areas that are visible to none

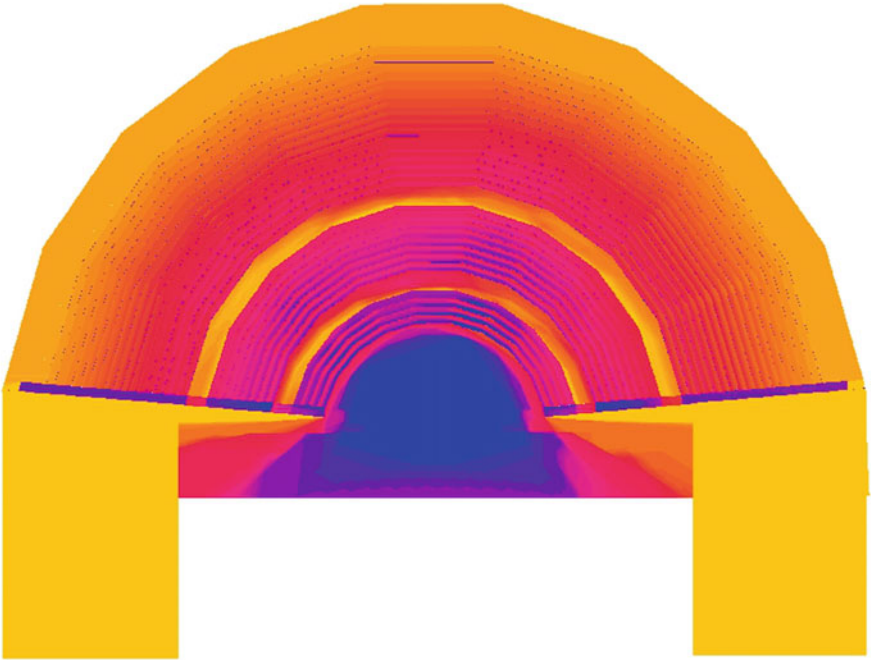

Fig. 6 Map of frequency of visibility of the theatre at the acropolis of Gortyna (model N.2). The blue colour indicates the areas that are visible by all observer points and the yellow colour indicates the areas that are visible to none

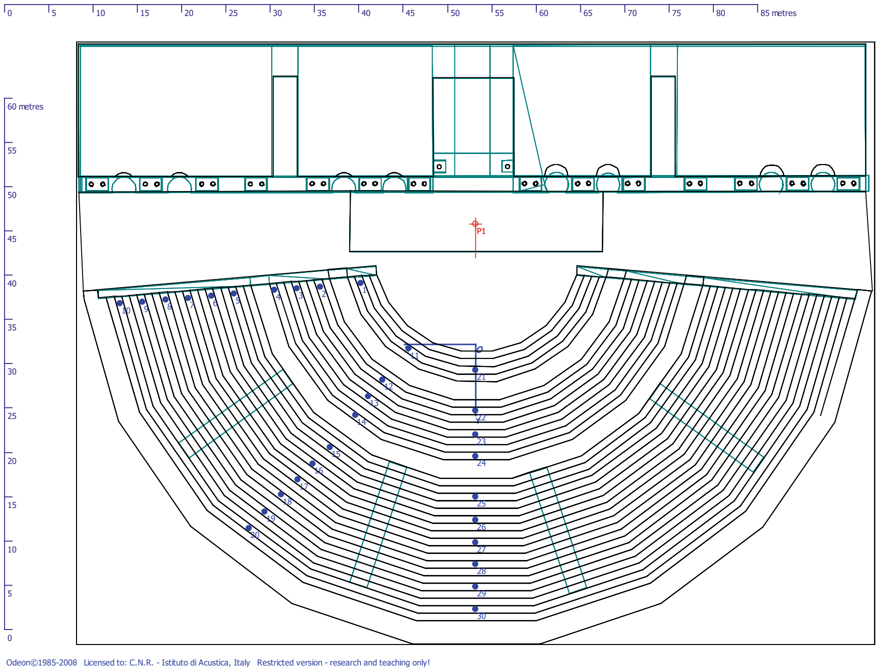

Fig. 7 Representation of model N.1 together with the receivers and the source in Odeon Room Acoustics

for RT, the difference between RT and EDT, C80 and D50, of the two 3D models. Table 1 points out that the reverberation time, in model N.1, is around 1 s and it is then suitable for spoken performances. The difference between reverberation time and the early decay time is between 0.18 and 0.44: it seems consistent with the analyses made in other theatres where the difference was between 0.2 and 0.4 (Gade and Angelakis 2006). The clarity is above 4 dB and the definition is above 0.57; both values indicate a space where speech is easy to comprehend. Moreover, the average value of the speech transmission index of model N.1 is 0.69, suggesting good intelligibility of the spoken language.

Table 1 Average values of all the receivers of RT, difference between RT and EDT, C80 and D50, at each frequency, of model N.1

	RT	RT-EDT	C80	D50
125 Hz	1.40	0.18	4	0.57
250 Hz	1.23	0.35	6.10	0.66
500 Hz	1.10	0.44	7.79	0.73
1000 Hz	1.04	0.37	7.56	0.72
2000 Hz	1	0.37	7.79	0.73

Table 2 Average values of all the receivers of RT, difference between RT and EDT, C80 and D50, at each frequency, of model N.2

	RT	RT-EDT	C80	D50
125 Hz	1.82	−0.1	0.64	0.42
250 Hz	1.65	−0.05	2.27	0.50
500 Hz	1.49	0.07	3.60	0.57
1000 Hz	1.43	0.11	3.60	0.57
2000 Hz	1.41	0.16	3.91	0.58

Table 2 shows that the reverberation time of model N.2 is between 1 and 2 s. The difference between reverberation time and the early decay time is singular, it is very low and does not conform to how it was demonstrated in the previous research above mentioned. The clarity is also anomalous. Its low-frequency values are under 3 dB, which would be suitable for musical performances, but its high-frequency values are above 3 dB (but not too much, between 3.60 and 3.91) as it is suggested for spoken performances. The definition has a similar trend as the clarity: at 125 Hz goes under 0.50 and then it raises till 0.58. The average value of the speech transmission index of model N.2 is 0.60.

The auralisation of several receivers was made for both models. Listening to the auralised files of model N.2, it is possible to perceive a slight echo that is enough to influence the good comprehension of speech. In the auralised file of model N.1, the echo is absent.

5 Discussion and Conclusion

The 3D visibility analysis demonstrated that the structure of model N.1 (the one with *parodoi* between cavea and scene building, and without portico in *summa* cavea) ensures the visibility of the central part of the stage to each spectator. High visibility of the stage is still maintained with the structure of model N.2 (characterised by cavea and scene building forming an enclosed space and by the portico in *summa* cavea), but the stage is not visible by all spectators. Such results may suggest that model N.1 is more reliable than model N.2 but we should also consider that maybe not every seat was supposed to be occupied and that maybe the side areas of the cavea, from which there is limited visibility, were not used. The virtual acoustics analysis seems to confirm the reliability of the reconstruction of model N.1 rather than the one of model N.2. All resulting values of each parameter analysed of model N.1, and the auralisation too, are consistent in demonstrating that such a space would be ideal for acting a spoken performance. While the values obtained from the virtual acoustics analysis of model N.2 do not indicate a clear identification of the possible role of that space, they are inconsistent among them and an echo is perceived from several auralised files in different positions of the seating area.

We may conclude that this research demonstrated that the Roman theatre at the acropolis of Gortyna maintained some Greek characteristics as the presence of the *parodoi* and the absence of the portico in *summa* cavea (Fig. 8). At the same time, we may consider that 3D visibility analysis and virtual acoustics analysis are tools that incite us to think about the architectural structure of the Roman theatres and about its exact function, rather than instruments useful to formulate new conclusive hypotheses. We should wonder if really everyone in a theatre was able to completely see the stage and if the performances were totally clear. We should also contemplate the possibility of mistakes made by the ancient architects. Moreover, we should not forget that, in particular in Roman times, the cavea of the theatres was organised according to the social status of the spectators, so there were probably privileged seats. At the same time, it is not realistic to think that the poorest groups of the society used to go to watch a performance without the possibility to see it and listen to it. 3D visibility analysis, virtual acoustics analysis and auralisation produce suggestions and encourage specialists to investigate more on some aspects. Furthermore, the comparisons of the results obtained analysing both Greek and Roman theatres would help us to understand if the architectural evolution of these monuments was also due to the need to enhance the visibility and the acoustics of these places of entertainment.

The combination of the three instruments is a further step to ensure valuable and meaningful research. However, improvements to this methodology need to be done. First of all, psychoacoustics needs to be considered in such kind of research since the

Fig. 8 Virtual reconstruction of the hypothetical architectural structure of the theatre

perception of sound (as for other senses) is subjected to different factors (age, gender, culture, memories, etc.) (Kolar 2013). To judge the auralised files more extensively and accurately, it would be necessary to create an evaluation test to be filled by a group of people of different ages, cultures and education. The questionnaire can be primarily based on three elements: the expectations on acoustical factors (how much they are considered important), the perception of sound in the different positions in the cavea (rating of annoyance or pleasure), the reaction to the sound (provoked feelings) (Yorukoglu and Kang 2017). Something else that should be considered is the background noise or any other sound that could happen during the performance, even if theatres were not generally placed in the crossroad of very dynamic and populated areas and the retaining wall of the Roman theatres were supposed to acoustically isolate the space from outside noises as stated by Canac. It would be interesting to test such scenario: recreating external soundscape (voices, animals and chariots) and also internal soundscapes (as hubbubs and background music) and including them in the auralisation to verify the quality of the sound and the comprehension of the performance.

This kind of methodology can be applied not only to theatres but also to amphitheatres, stadiums, circuses and all other buildings or monuments where visibility and acoustics play an important role.

Moreover, the results of such kind of study can be useful not only to investigate and interpret the architectural structure of some monuments, but they can be used as an educational instrument as well. The visualisation through 3D models and the listening of auralised files can facilitate the understanding and the memorisation of historical contexts by non-experts. These elements have been combined to develop a Virtual Reality application for head-mounted display to be used onsite or in the museums (Manzetti 2018b). This experience can be improved and can be made more meaningful by stimulating the sense of smell as well (Day 2017).

The research and the methodology presented here have the aim to demonstrate the advantages to adopt an interdisciplinary and multisensory approach. Some results, such as the level of visibility and the acoustics values of monuments or sites that are not fully preserved, can be obtained until now only with this kind of approach. The information collected through this methodology not only enhances our knowledge about ancient buildings but also raises new questions and stimulates new investigations. Hopefully, this methodology will be integrated in the future with approaches that consider the rest of the senses (smell, touch, skin and body sensations) to improve the accuracy of the research and also to expand our vision of ancient societies and not to be limited to the modern conception of the world.

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References

Barresi, P., 2004. Gortyna: la sistemazione del teatro all'Acropoli in età Severiana, in: Creta Romana e Protobizantina, Atti Del Convegno (Iraklion 2000). Bottega D'Erasmo, Padova, pp. 557–572.
Beschi, L., 1999. Onorio Belli a Creta: un manoscritto inedito della Scuola Archeologica Italiana di Atene (1587). Scuola Archeologica Italiana di Atene, Atene.
Betts, E., 2017. Senses of the Empire. Multisensory approaches to Roman Culture. Routledge Taylor & Francis Group, London and New York.
Bieber, M., 1981. The History of the Greek and Roman Theatre. Princeton University Press, Princeton.
Bishop, I.D., Wherrett, J.R., Miller, D.R., 2000. Using Image Depth Variables as Predictors of Visual Quality. Environ Plann B Plann Des 27, 865–875. https://doi.org/10.1068/b26101.
Bonetto, J., Francisci, D., 2014. Il teatro del Pythion di Gortina: storia di un teatro romano a Creta, in: Proceedings XVIII International Congress of Classical Archaeology. Presented at the Centro y periferia en el mundo clasico, Museo Nacional de Arte Romano, Merida, pp. 941–944.
Bonetto, J., Francisci, D., Mazzochin, S., 2019. Gortyna IX. Il teatro del Pythion. Scavi e ricerche 2001–2013., Monografie della SAIA. Scuola Archeologica Italiana di Atene, Atene.
Canac, F., 1967. L'acoustique des théatres antiques. Ses enseignements. Centre National de la Recherche Scientifique, Paris.
Christensen, Koutsouris, 2015. Odeon Room Acoustics Software, Version 13, Full User's Manual.
Day, J., 2017. Scents of place and colours of smell. Fragranced entertainmentin ancient Rome, in: Senses of the Empire. Multisensory Approaches to Roman Culture. Routledge Taylor & Francis Group, London and New York.
Day, J., 2013. Making Senses of the Past: Toward a Sensory Archaeology. Southern Illinois University Press.
Devereux, P., 2001. Stone Age Soundtracks: The Acoustic Archaeology of Ancient Sites. Vega, London.
Erdogan, S., 2006. ERATO Project Symposium. Audio visual conservation of the architectural spaces in virtual environment. Proceedings. Yildiz technical University, Istanbul, Turkey.
Falkener, E., 1854. A description of some important theatres and other remains in Crete, from a ms. History of Candia by Onorio Belli in 1586, Supplement to the Museum of Classical Antiquities. Trübner & Co., London.
Fisher, P., Farrelly, C., Maddocks, A., Ruggles, C., 1997. Spatial Analysis of Visible Areas from the Bronze Age Cairns of Mull. Journal of Archaeological Science 24, 581–592.
Foteinou, A., Murphy, D.T., 2011. Perceptual validation in the acoustics modelling and auralization of heritage sites: the acoustic measurement and modelling of St Margaret's Church, York, UK, in: Proceedings of The Acoustics of Ancient Theatres Conference. Presented at the The Acoustics of the Ancient Theatres Conference, Patras.
Frieman, C., Gillings, M., 2007. Seeing is perceiving? World Archaeology 39, 4–16. https://doi.org/10.1080/00438240601133816.
Gade, Angelakis, 2006. Acoustics of ancient Greek and Roman theatres in use today. The Journal of Acoustical Society of America 120, 3148–3156.
Hamilakis, Y., 2013. Archaeology and the Senses. Human Experience, Memory, and Affect. Cambridge University Press.
Hamilakis, Y., 2011. Archaeologies of the Senses [WWW Document]. The Oxford Handbook of the Archaeology of Ritual and Religion. https://doi.org/10.1093/oxfordhb/9780199232444.013.0016.
Iannace, G., Maffei, L., Aletta, F., 2011a. Computer simulation of the effect of the audience on the acoustics of the Roman theatre of Beneventum (Italy), in: Proceedings of The Acoustics of Ancient Theatres Conference. Patras.
Iannace, G., Maffei, L., Trematerra, P., 2011b. The Acoustics Evolution of the large Theatre of Pompeii, in: Proceedings of The Acoustics of Ancient Theatres Conference. Patras.

Kanta, A., Lirintzis, A., Nikolopoulou, K., 2014. Το Μεγάλο Θέατρο της Γόρτυνας-Τα πρώτα αποτελέσματα, in: 1° ΔΙΕΘΝΕς ΔΙΕΠΙΣΤΗΜΟΝΙΚΟ ΣΥΝΕΔΡΙΟ ΓΟΡΤΥΝΑΣ. Presented at the Έν Γορτυνη και 'Αρκαδια εγενετο...,' Εφη Ψιλακη, Μανωλης Δρακακης, Ηρακλειο, pp. 91–99.

Kolar, M., 2013. Archaeological Psychoacoustics at Chavin du Huantar, Peru (Doctoral dissertation). Stanford University, Stanford.

Lake, M.W., Woodman, P.E., 2003. Visibility Studies in Archaeology: A Review and Case Study. Environ Plann B Plann Des 30, 689–707. https://doi.org/10.1068/b29122.

Landeschi, G., Dell'Unto, N., Lundqvist, K., Ferdani, D., Campanaro, D.M., Leander Touati, A.-M., 2016. 3D-GIS as a platform for visual analysis: Investigating a Pompeian house. Journal of Archaeological Science 65, 103–113. https://doi.org/10.1016/j.jas.2015.11.002.

Lokki, T., Southern, A., Siltanen, S., Savioja, L., 2011. Studies of Epidaurus with a hybrid room acoustics modeling method, in: Proceedings of The Acoustics of Ancient Theatres Conference. Patras.

Loots, L., Nackaerts, K., Waelkens, M., 1999. Fuzzy viewshed analysis of the Hellenistic city defence system at Sagalassos, Turkey. Presented at the Archaeology in the age of the internet - CAA97: computer applications and quantitative methods in archaeology. 25th anniversary conference, British archaeological reports, Birmingham, p. ?–?.

Lopez-Menchero Bendicho, V.M., 2013. International Guidelines for Virtual Archaeology: The Seville Principles, in: Good Practice in Archaeological Diagnostics., Natural Science in Archaeology. Springer, Switzerland, pp. 269–283.

Manzetti, M.C., 2018a. Experiencing an Ancient Performances in a Roman theatre, in: Archaeoacoustics III - More on the Archaeology of Sound: Publication of Papers from the Third International Multi-Disciplinary Conference. Presented at the Archaeoacoustics III, The OTS Foundation, Myakka City, Florida, pp. 122–126.

Manzetti, M.C., 2018b. An interdisciplinary approach for the study and the valorization of the Roman theatres of Crete (Doctoral dissertation). School of Architectural Engineering, Technical University of Crete, Chania, Greece.

Manzetti, M.C., Parthenios, P., Sarris, A., 2015. Integrating traditional methods with new technologies, in: 2015 Digital Heritage. Presented at the 2015 Digital Heritage, pp. 173–176. https://doi.org/10.1109/DigitalHeritage.2015.7419480.

Morgan, M.H., 1914. Vitruvius. The ten books on architecture. Harvard University Press, Cambridge.

Paliou, E., Knight, D.J., 2013. Mapping the senses: Perceptual and Social aspects of Late Antique Liturgy in San Vitale, Ravenna, in: Proceedings of CAA 2010, Computer Applications and Quantitative Methods in Archaeology, International Conference, Granada 6-9 April, 2010. Presented at the Computer Applications and Quantitative methods in Archaeology, F. Contreras, M. Farjas and F.J. Melero, Granada, Spain, pp. 229–236.

Paliou, E., Wheatley, D., Earl, G., 2011. Three-dimensional visibility analysis of architectural spaces: iconography and visibility of the wall paintings of Xeste 3 (Late Bronze Age Akrotiri). Journal of Archaeological Science 38, 375–386. https://doi.org/10.1016/j.jas.2010.09.016.

Pappalardo, U., 2007. Teatri Greci e Romani. Arsenale Editore, San Giovanni Lupatoto, Verona.

Pashley, R., 1837. Travels in Crete. John Murray, London.

Pitton de Tournefort, J., 1717. Relation d'un voyage du Levant fait par ordre du Roy. De l'Imprimerie Royale, Paris.

Pococke, R., 1745. Description of the East and some other countries. Bowyer W., London.

Reilly, P., 1991. Towards a Virtual Archaeology, in: Computer Applications and Quantitative Methods in Archaeology 1990, 565. Tempus Reparatum, Oxford, pp. 132–139.

Ruggles, C.L.N., Medyckyj-Scott, D.J., Gruffydd, A., 1993. Multiple viewshed analysis using GIS and its archaeological applications: a case study in northern Mull, in: Andresen, J., T. Madsen and I. Scollar (Eds.), Computing the Past. Presented at the Computer Applications and Quantitative Methods in Archaeology. CAA92, Aarhus University Press, Aarhus, pp. 125–132.

Sarris, A., Papadopoulos, N., 2010. Τεχνική Έκθεση της Γεωφυσικής Έρευνας & Χαρτογράφησης των Αρχαίων Θεάτρων της Ιεράπετρα; & Κουφονησίου (2010). Εργαστήριο Γεωφυσικής-Δορυφορικής Τηλεπισκόπησης & Αρχαιοπεριβάλλοντος. Ινστιτούτο Μεσογειακών Σπουδών, Ρέθυμνο.
Scarre, C., Lawson, G., 2006. Archaeoacoustics, McDonald Institute Monographs. ed. McDonald Instituire for Archaeological Research, Cambridge.
Scuola Archeologica Italiana di Atene, 1984. Creta antica. Cento anni di archeologia italiana, 1884–1984. De Luca, Roma.
Spagnolo, R., 2014. Manuale di acustica applicata. CittàStudi, Torino.
Spratt, T.A.B., 1865. Travels and researches in Crete. John Van Voorst, London.
Taramelli, A., 1902. Cretan Expedition: XXI Gortyna. American Journal of Archaeology 6, 101–165.
Tufte, E., 1990. Envisioning Information. Graphic Press, Michigan University.
Vana Niniou-Kindeli, Chatzidakis, N., 2016. The Roman theatre at Aptera: a preliminary report, in: Roman Crete: New Perspectives. Oxford: Oxbow Books, pp. 127–153.
Veitch, J., 2017. Soundscape of the street. Architectural acoustics in Ostia, in: Senses of the Empire: Multisensory Approaches to Roman Culture. Routledge Taylor & Francis Group, New York, NY, USA, pp. 54–70.
Wheatley, D., 2014. Connecting landscapes with built environments: visibility analysis, scale and the senses, in: Spatial Analysis and Social Spaces. Interdisciplinary Approaches to the Interpretation of Prehistoric and Historic Built Environments. De Gruyter, Boston, pp. 115–134.
Wheatley, D., 1995. Cumulative viewshed analysis: a GIS-based method for investigating intervisibility, and its archaeological application, in: Archaeology and GIS: A European Perspective. Routlege, London, pp. 171–186.
Yorukoglu, P.N.D., Kang, J., 2017. Development and testing of Indoor Soundscape Questionnaire for evaluating contextual experience in public spaces. Building Acoustics 24, 307–324.

Maria Cristina Manzetti is an archaeologist with a Ph.D. in architecture. She is currently a YUFE postdoc researcher at the Department of History and Archaeology at the University of Cyprus. Her specialty is virtual analyses in archaeological contexts.