PAN
ARCHIVES OF ACOUSTICS
Vol. **45**, No. 2, pp. 181–208 (2020)
DOI: 10.24425/aoa.2020.132494

Review Paper

Exploring the Acoustics of Ancient Open-Air Theatres

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(*received August 25, 2019; accepted January 9, 2020*)

The theatres of Antiquity, Greek and Roman, constitute public buildings of the utmost importance in the history of Western culture and in universal cultural heritage. Many of these spaces are being used for their original function with or without only minor adaptations. If they are well preserved and/or restored, these performance buildings attract large audiences to representations of classical and contemporary plays, thereby serving the purpose for which they were built in the Ancient Age. These theatres bear witness to the existing relationship between architectural work, visual and acoustic experience, and dramatic art. Although the majority are located in the Mediterranean region, these structures were also built in the major cities of the ancient world in Europe, the Middle East, northern Africa, and beyond. This paper aims to summarise and critically review research published in the literature regarding their acoustic aspects, with particular emphasis on Roman theatres. These pieces of research emphasize the importance of the diffraction of sound in the tiers of the *cavea* and the good intelligibility for speech of the Greco-Roman theatre.

Keywords: acoustics of theatres; classical theatre acoustics; open-air theatre; heritage acoustics.

1. Introduction

Ancient Greek and Roman theatres form part of the acoustic and cultural heritage disseminated mostly in coastal countries along the Mediterranean shore and in other regions in the major cities of the ancient world of Europe, the Middle East, northern Africa, and beyond. This area extends: from east to west, from the Greek city of Alexandria of Oxo (Ai Khanoum, northen Afghanistan), in the confines of the Indian subcontinent, to the Roman theatre of Lisbon, today non-existent; and, from north to south, from the Roman province in England to the Greek city of Ptolemais Hermiou in Upper Egypt (Mourjopoulos, Fausti, 2013). According to Mourjopoulos and Fausti (2013), to date, 741 structures of ancient theatres have been identified and documented, of which 194 correspond to the first Greek theatres, while 425 theatres and 46 odeons belong to the Roman era, and the remaining 76 cannot be precisely identified as either Greek or Roman. In many cases, only vestiges of these structures are present. In consonance with the origins and zones of influence of the Greek and Roman cultures, there is a great density of these structures in Italy, southern Greece, Turkey, and in certain regions of northern France (Fig. 1).

As stated by Berardi *et al.* (2016), a census published in 2010 showed that, in Italy, there are the remains of 224 ancient theatres and *odea* (or *odeia*), built during the Greek and Roman periods. Within this large sample, 191 theatres are still architecturally identifiable as theatrical structures, of which almost half are used today for drama, dance, and musical festivals. Although it remains a controversial issue, the conscious and sustainable re-adaptation of ancient theatres to current performances is a theme of special interest in Italy, mainly due to its wide classical heritage.

The evolution of these ancient theatres begins in the 6th century BC, and the time of transition from the Hellenistic period to the Roman period is considered to have taken place around the first half of the 1st century BC. These buildings were originally closely linked to religious rituals and later evolved independently of religion, culminating in performances by actors and a choir (including recitals, singing, and dancing), with all the features of a theatrical production. The emergence and historical development of the theatre as an artistic expression was affected by the structure and

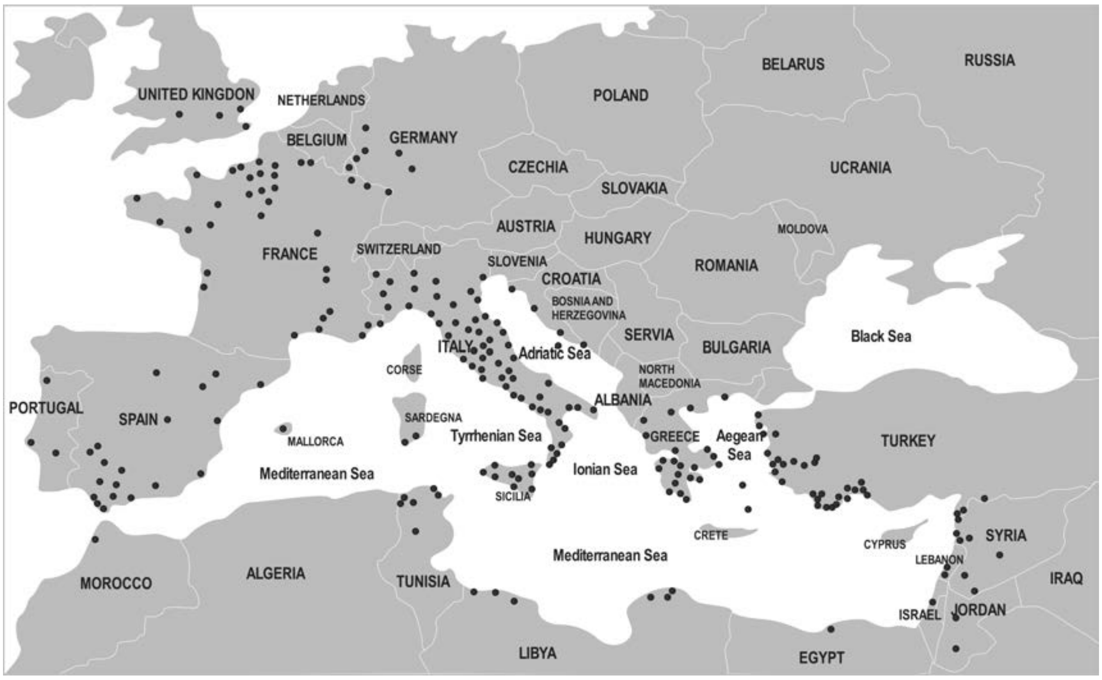

Fig. 1. Theatres of Antiquity in Europe, the Middle East, and northern Africa.

the acoustic properties of the open-air theatres; these classical theatres constitute the earliest witnesses of the inter-relationship between architecture, acoustics, and theatrical performances.

More recently, in addition to the long-term interest by historians and archaeologists, increasing attention has been paid to the acoustics of ancient theatres in the last decade (acoustics is an immaterial aspect of the space; its acoustic heritage must be taken into account when reconstructing in accordance with the possible alternatives). In addition to this practical interest, the theoretical study of sound propagation in these unroofed spaces holds great significance for scientific knowledge.

The acoustics of classical open-air theatres and odeons impress not only visitors and spectators but also technicians. Likewise, since 2000, interest has been renewed in the wide use of methods that use simulation software, since virtual acoustics and virtual reality enable the recreation of the original acoustics of the theatre and the comparison of different renovation proposals and refurbishments of acoustic conditioning, whether they be ephemeral or permanent for polyvalent purposes.

In this context, it is worth highlighting several milestones in current knowledge and in the dissemination of the acoustics of the classical theatres of Antiquity, such as the European ERATO project, which responds to the acronym for Identification, Evaluation, and Revival of the Acoustical Heritage of Ancient Theatres and Odea (Rindel, 2013). Its objective was to investigate the acoustics of classical open-air theatres and *odea* using virtual reconstruction by means of computational models of the spaces, made in accordance with the archaeological information available. Musical instruments of the time and short musical pieces were reconstructed and recorded in an anechoic environment to be auralised in these virtual environments. The project was financed by the European Union with a duration of three years (2003–2005) and its research group included 5 European universities and research institutions, a Turkish university, and a Jordanian university, whose aim involved the conservation and restoration of the buildings of the architectural heritage, which took into account their acoustic characteristics. Five spaces were selected for the virtual reconstruction: three Roman theatres and two *odea*, which are discussed later in this paper.

Furthermore, on a more local scale, the Italian project ATLAS stands out (Pompoli, Gugliermetti, 2006) as a research project of national interest dedicated to safeguarding the acoustic and visual aspects of the old theatres. The ATLAS project (Ancient Theatres Lighting and Acoustics Support) is cofunded by MIUR (Italian Ministry of University and Research).

Two other events worthy of mention are, on the one hand, the International Congress held in the University of Patras (Greece), in September 2011: The Acoustics of Ancient Theatres (2011). This congress brought together experts in acoustics and other fields of engineering to present and discuss all aspects and findings related to the acoustic properties of these unique ancient monuments, which are largely located around the Mediterranean region and are often used for public performances of plays, drama, speech, and music. On the other hand, the other event deserving mention is that of the publication of the special section of volume 1 of the year 2013, of the Acta Acustica United with Acustica journal (Mourjopoulos, Fausti, 2013). This journal publishes, in a more extensive way, the most relevant pieces of research of the previous congress, and covers a wide range of topics of general scope, such as the work of Blauert (2013), which analyses the conceptual aspects of the qualitative acoustic experience in scenic spaces, and examines the processes of the areas of psychoacoustics, sensory psychology, physics, and communication sciences that contribute towards the formation of sound/aural quality. Likewise, the work by Cocchi (2013), which, with a precise analysis of both the acoustic science in antiquity and the disposition of the Greek and Roman theatres and articulated with a historical background on the behaviour of people, shows that the design of these theatres was based on reasons other than the objective of meeting the best acoustic conditions for the audience. Other more specific congress contributions are discussed later in this paper.

This work aims to provide a critical review of the acoustics of all the classical theatres that have hitherto been investigated, with special interest focused on the acoustics of outdoor Roman theatres.

Given the large time span over which the papers mentioned herein were produced, the nomenclature for the acoustic parameters they use may vary. For the sake of consistency, the notation specified in the current version of the standard (ISO 3382-1:2009(E)) has been adopted throughout this paper.

2. Greek Theatres

2.1. Early Cultures. Archaic period (800 BC – 500 BC)

According to Long (2006), in primitive societies, the first meeting places would arise in open natural and wide areas, although uncertainty remains regarding the suitability of the chosen space to the purpose of the assembly. As the society grew and since the collective activities that brought together a certain number of individuals were polyvalent (political, military, religious, spectacles), the audience was arranged in concentric circles with the speaker in the centre. Due to the directionality of the human voice and the divergence law of sound, an arrangement of seats according to this polar pattern of the human voice was experimentally established and natural locations were sought that would allow good intelligibility, unobstructed vision, and direct sound. That is to say, steps were constructed in concentric circles in front of the speaker. These constructed tiers later evolved and acquired new functions, when society itself needed scenarios of a more specialized nature for the development of civic life. These structures became permanent, where the entrance and exit of the audience were facilitated by corridors and stairs: theatres built on the hill slopes were born.

2.2. The Greek period (500 BC – 150 BC)

Theatre construction is an architectural achievement of Greek civilization; their simplicity of design, with a nearly circular seating layout, enables a balance between functionality and aesthetics. They were also an essential element of every urban centre in the Classical period.

Early wooden theatre structures date back to the 6th century BC and are known only from literary sources and paintings. The construction of classical Greek stone theatres runs from the 5th century BC to the 3rd century BC. It is relatively easy to identify at least a hundred theatres constructed in this period, and following the Greek period, there are innumerable Hellenistic and Roman theatres.

Classical Greek theatres are present throughout continental and insular Greece, as well as in Magna Greece (name given in Antiquity to the territory occupied by the Greek colonists in the south of the Italian peninsula and in Sicily, where numerous polis were founded which traded with their metropolis) and in Asia Minor. These were open-air performance spaces linked to religious rituals and celebrations (Dionysos), and to activities of the institution of democracy, and were also used for the performance of drama. According to Knudsen (1932), the maximum distance to hear an oral message (without background noise) is 42 m in the frontal direction, 30 m laterally, and 17 m from behind, due to the directional characteristics of the human voice. In classical Greek theatres, these distances are susceptibly greater, in the order of up to 70 m; the surprisingly good intelligibility in the furthest steps, however, is due to the reinforcement of the direct sound by the first reflections generated in the orchestra (with delays of less than 50 ms).

The seating plan was in the shape of a segment of a circle, slightly more than 180°, often on the side of a hill facing the sea. Another distinctive feature of Greek theatres was the steep slope of their stands, between 20° and 34°, which provided good sight lines and reduced grazing incidence.

In order to illustrate a general theatre, Fig. 2 shows the three discrete parts and nomenclature of a Greek theatre: the audience seating area (*koilon*); the place for the choir (*orchestra*); and the stage building (*skené*). Both for their architecture and their related acoustic functionality, Greek theatres can be considered the starting point of theatre history and design (Izenour, 1996). The acoustical character of ancient theatres has been the subject of several specific studies in the past. One prominent theoretical contribution in this regard is the book by Canac (1967), where the

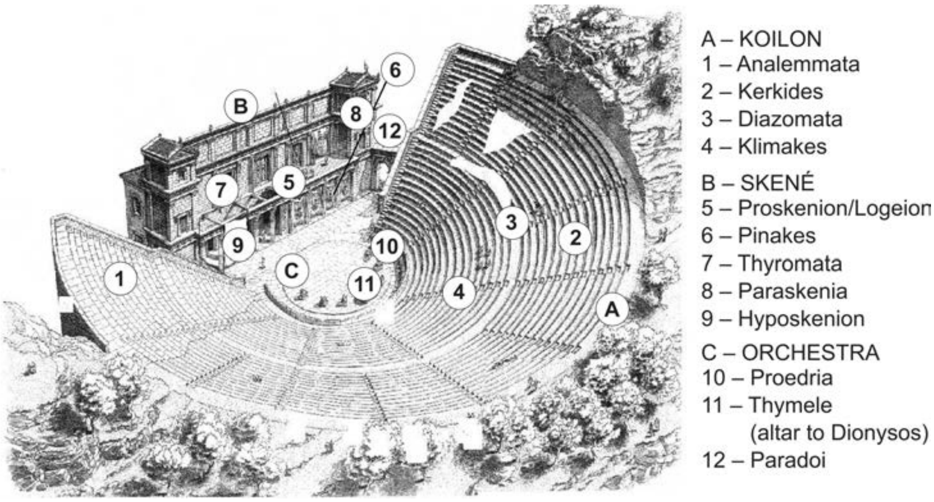

Fig. 2. Parts of a Greek theatre (source: adapted from https://commons.wikimedia.org/wiki/File:GriechTheater2.PNG, author: Flammingo (CC BY-SA 3.0)).

image source approach was applied. In this study, a basic energy equation for the sound level was developed as a function of the hearing angle and of the slope of the *koilon*. This is the case, for instance, for the design of the *koilon* and of the Greek technique of increasing its slope towards the farthest positions, which is also regarded as a valid rule for modern theatre design (Tzekakis, Schubert, 1999).

One of the best-preserved examples of Greco-Hellenistic theatres is that built at Epidaurus in the northeastern Peloponnese in 330 BC, about the time of Aristotle. The name "Epidaurus" indicates a place affected by the wind. The theatre was constructed by the architect Polykleitos the Younger and, during Roman times, the theatre (unlike many Greek theatres) did not suffer any modifications. A sketch of the ground plan is shown in Fig. 3a: its fan shape covers 210° and it is worth noting that this theatre, with a capacity of approximately 17,000 people, is still in use (Fig. 3b).

On the acoustics of the large theatre of Epidaurus, numerous pieces of work have been published. For example, in the early work of Papathanasopoulos (1965), sound level, speech intelligibility, and reverberation time are analysed to conclude that the reason for its good acoustics lies in the achievement of Greek designers to optimize the plan and section of theatres. On the basis of score tests for speech articulation, Shankland (1973) later hypothesized that the acoustic excellence of Epidaurus and other Greek theatres (Shankland, 1968) is due to the spectrum of early reflected and scattered sound rendered by the boundary steps of the *koilon* and due to the audience being favoured by the perfection of the seating geometry in this theatre. In his paper, the author also makes an assessment of the effect of interference with hearing conditions due to outdoor noise (traffic, streetlife, wind...) and indoor noise in these open-air theatres.

Vassilantonopoulos and Mourjopoulos (2003) then presented a study on classical theatres, which is a continuation of the methodology used by those authors to study other missing Greek public buildings of historic significance, whose architectural features have been well-defined in historical sources and through archaeological research (Vassilantonopoulos, Mourjopoulos, 2001). For the case of Epidaurus and 2 other theatres (the odea of Dodoni and Patras), these authors utilised computer-aided simulation and building acoustics combined with virtual acoustic representation (auralisation) to provide a direct aural impression of their response to speech and/or music signals.

Through CATT-Acoustic software (Dalenbäck, 2011), a comparison is made of the three theatres studied, while considering two positions of the sound source, first with no audience and then with full audience conditions, and under conditions of low ambient noise and then high ambient noise with the full audience. The acoustic evaluation takes place by means of analysis of the acoustic parameters studied (SPL, as a sum of the 125–4000 Hz band components, G, T_s, D_{50}, C_{80}, RASTI, and J_{LFC}) combined with listening audio tests under conditions of controlled auralisation experiments. The study verified that these theatres provide a remarkable acoustic performance, which should be considered as an achievement of ancient acoustic technology. Furthermore, Gade and Angelakis (2006) measured and created a computer model of the large and small ancient theatres in Epidaurus in order to discuss their potential in the light of acoustic performance requirements for modern use.

In the research by Declercq and Dekeyser (2007a), the authors point out that a number of "explanations" for the excellent acoustics of Epidaurus have been posited: the sound transported by the wind; the

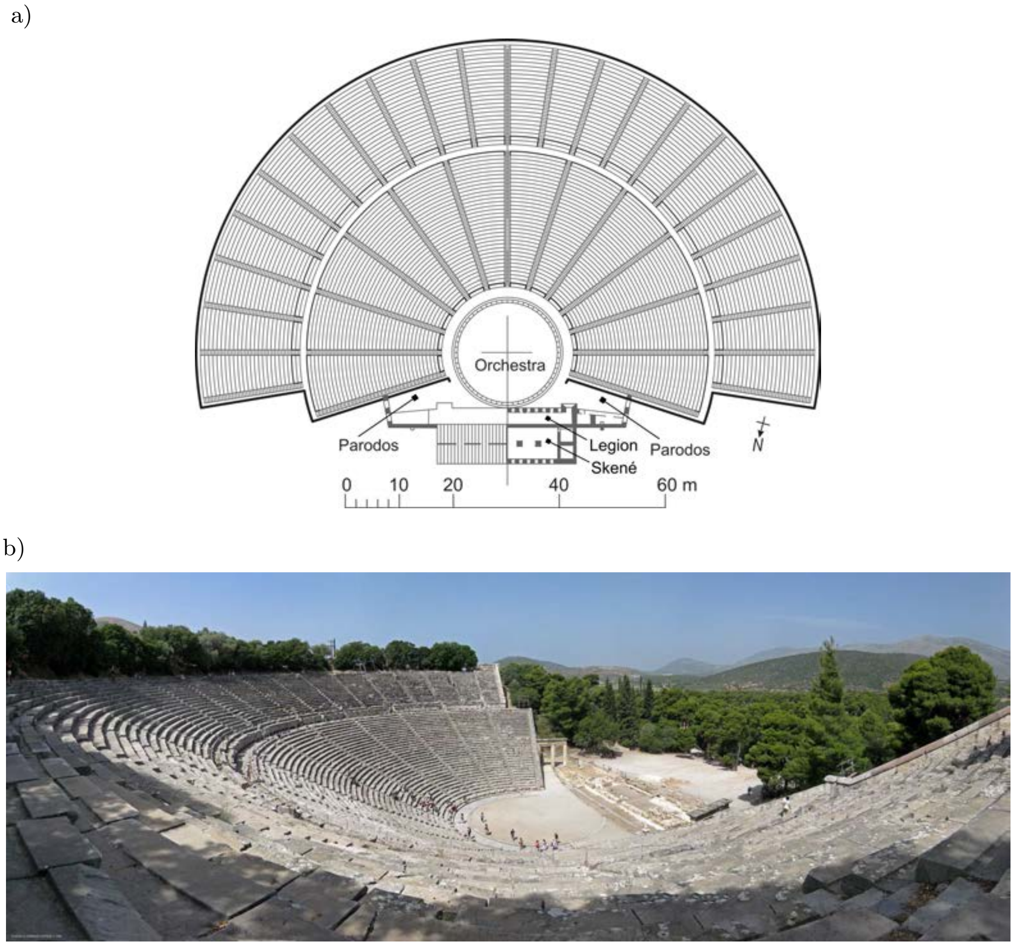

Fig. 3. The Large Epidaurus Theatre: a) ground plan; b) a photograph of the venue (author: Gonzalo Serrano (CC BY-NC 2.0), source: https://www.flickr.com/photos/gserrano22/6961616996/in/photolist-PL5JVq-5yMeg4-bBb7cf-7MPHMt-v7Rov-7MPGQV-6XgnC1-5PirNN-2g9r1Lk-acoooJ-6XgnNC-7MPJG8-duasxJ-duDajZ-7zZRp9-7zW5VT-duDdta-du-JMmS-xZC9Nu-7zZR5o-acoikC).

significance of the rhythm of speech of Hellenistic poems and plays composed by classical authors; and the focusing effect of the sound produced by actors wearing masks. However, the opposite effects of the three conditions also generate a wonderful quality of sound in the theatre, and hence these reasons must be discarded. Izenour (1996) points out that the acoustics are of such high quality due to the clear path between the speaker and the audience. Declercq and Dekeyser (2007a) numerically prove that the effect of diffraction on the seat rows is a more important effect than the "clear path effect". By means of acoustic simulation, these authors (Declercq, Dekeyser, 2007a) model the Greek theatre of Epidaurus, and incorporate multiple diffraction orders therein, concluding that the sound is scattered backwards from the tiers of the *koilon* towards the audience, so that the audience receives the sound, not only from the front, but also backscattered from behind. In addition, they show that such retro-dispersions amplify the high frequencies more (above 500 Hz, which is the upper limit for wind noise), which is essential for the intelligibility of the spoken word. The numerical model presented reveals that rows of seats play a major role in the acoustics of the theatre, at least when it is not completely occupied by spectators, since the rows constitute a corrugated surface that works as a filter in accordance with the periodicity of the rows of observed seats.

Declercq and Dekeyser (2007b) also apply the numerical model to other theatres of Antiquity, and observe that the slope of the cavea bears no influence on the frequency values where the amplified frequency band appears and that there are no significant differences between the acoustics in summer and winter.

Along these lines, Economou and Charalampous (2013) also study the sound diffraction effects of circular rows of stone steps. They combine sound measurements taken at the ancient theatre of Kourion in Cyprus with the results of an acoustical model in a commercial software application which handles sound diffraction and reflections of high orders. Moreover, Psarras *et al.* (2013) present extensive results for acoustic and meteorological data for the theatre of Epidaurus for multiple source-receiver combinations with the degree of occupancy. Their analysis of the early part of impulse responses in the time and frequency domain confirm the pattern of early reflections proposed by Lokki *el al.* (2013) and also confirm the amplification above 500 Hz predicted by Declercq and Dekeyser's model, although not their predictions for low-frequency attenuation. Monaural acoustic indices (D_{50}, C_{80}, STI-RASTI, T_{30}, and G) and binaural parameters (IACC) not only confirm the high speech intelligibility throughout the vast audience area and the non-significant effect from environmental factors, such as temperature, humidity, and variation of wind, but also confirm the constancy in speech intelligibility with the presence of audience.

In research by Lokki *et al.* (2013), the authors develop a 3D model of the lower *koilon* of the theatre of Epidaurus. This was simulated for low frequencies up to 1000 Hz via a finite-difference time domain (FDTD) technique, which is able to predict diffraction and interference. The high frequencies are simulated via a beam-tracing method. The reasonable agreement between the results of the impulse responses in the virtual model and the experimental results from Vassilantonopoulos *et al.* (2011) (the prediction results are compared to real measurements and visualized with various methods both in the time domain and in the frequency domain) validates the model on performing the simulation with the wall of the stage that no longer exists. The early parts of the computed impulse responses are analysed to clarify the well-known acoustics for speech in the ancient theatres. Based on the analysis of the *in-situ* measurements, visits, and simulations of this study, the marvellous acoustics for speech of Epidaurus could be explained by the authors as follows: the strong sound and high speech intelligibility requires a sufficiently high signal-to-noise ratio. Epidaurus is located in the peaceful countryside in Greece. Therefore, the background noise in the venue is considerably low and the signal-to-noise ratio is reasonably high, especially in ancient times when the stage acted as a barrier to noise from the valley.

In addition to the unobstructed direct sound field, the early reflections are crucial for good speech intelligibility. The reflections from the stage wall, orchestra, rows of seating, and backscattering of the rows of seating arrive to the listener considerably soon after the arrival of the direct sound. In addition, these reflections are all from hard and reasonably flat surfaces, and are therefore well fused to the direct sound, resulting in a much stronger and louder sound. A visualization from a 2D FDTD simulation clearly shows all these components: the direct sound, ground reflection, stage back-wall reflection and its ground reflection, and finally the backscattering from the rows of seating. Furthermore, all these components of the sound field are visible even in the upper *koilon*.

As a conclusion on the topic of this spectacular theatre, it should be mentioned that, inspired by the theatre in Epidaurus, the Greek Theatre (in Catalan, *Teatre Grec*) is an open-air theatre located on the mountain of Montjuic, in the Spanish city of Barcelona, Catalonia. It was designed and built in 1929 on the occasion of the International Exhibition of Barcelona by the architects R. Reventós and N.M. Rubió.

Regarding other Greek theatres, Gullo *et al.* (2008) published results of measured records in five source positions of the sound field of the ancient theatre of Syracuse in Sicily. From the data recorded, room acoustic parameters were evaluated together with spectral analysis. Bo *et al.* (2016) also published results of an acoustic campaign in the theatre of Tyndaris (Sicily) where the calibration of the virtual acoustic model refers to objective parameters and to the temporal and energy components of the impulse responses. Recently Bo *et al.* (2018) investigated the accuracy of acoustical measurements and prediction models related to the ancient open-air theatre of Syracuse, Sicily. The methodology employed by the authors is based on an experimental acoustic campaign in accordance with the procedure established in the standard (ISO 3382-1:2009(E)) in the unoccupied state. Firecrackers were used as impulsive signals since there was a high level of background noise in the theatre. The acoustic parameters of reverberation time (T_{20}), clarity (C_{80}), and sound strength (G) were obtained from the IRs measured at each source-receiver combination and for two sound-source positions. For the acoustic simulation for the first time in an open-air theatre, the authors employed and compared the results of two software tools, ODEON (Christensen, Koutsouris, 2015) and CATT-Acoustic (Dalenbäck, 2011), both based on geometrical acoustic algorithms. The differences between measured and simulated results were analysed in terms of the Just Noticeable Differences (JNDs) of each acoustic parameter, where the tuning of the simulation model for the two software tools was based on the uncertainty in the input values of the coefficients of sound absorption, α, and sound scattering, s, of the *koilon* surface, for all receivers and for mid-frequency averages of the acoustic parameters. For this calibration, 20 combinations of the two coefficients were analysed (4 absorption coefficients and 5 scattering coefficients). Other sources of uncertainties in the computer-aided programmes, such as the run-to-run variations and number of rays, have also been analysed and the results obtained have all been found to be either under or at commonly accepted limit values of JNDs.

The authors reported the limitation of the simulation software for the open-air theatres and described how the best match between simulated and experimental results implies different values of the acoustic coefficients for the two software tools, where the variability of the results is related to the algorithms employed for the approximation of the acoustic phenomenon of sound absorption and sound scattering (Dalenbäck, 1996).

The uncertainty analysis carried out by the authors on the simulations of the Syracuse theatre shows that the results of the input variability of α and s depend on the acoustic parameter: it is lower than one JND for T_{20} and C_{80} when ODEON software is considered, and is lower than one JND for G when both types of software are considered.

Apart from T_{20}, ODEON software is more sensitive to variations in sound absorption than in sound scattering, while the opposite occurs for CATT-Acoustic; comparable behaviour of the simulated values of G has been shown for both types of software, and G has been found to be the most suitable parameter for the calibration of the open-air theatre model.

Likewise, the authors provide several recommendations for the implementation of experimental measures in these unroofed theatres into the campaign on the basis of measurement conditions, measurement procedures, and of the evaluation of sections of decay curves of ISO 3382-1 (2009).

2.3. Acoustic and architectural evolution from the Greek theatre to the Roman theatre

The investigations into the architectural evolution of ancient performance spaces are scattered across various fields of knowledge, such as archaeology, drama, architecture, history of music, and acoustics: of those that focus on acoustics, various articles can be highlighted. Chourmouziadou and Kang (2008) study the evolution of the acoustics of classical theatres built in different eras by means of computational modelling: from the early forms, the Minoan (20th–15th BC) and the Pre-Aeschylean (15th–6th BC) in the Pre-archaic and Archaic period; to the Classical Greek created in the 5th century BC; its descendant, the Hellenistic theatre; and subsequently the Roman Theatre. Their hypothesis proposes that changes in forms and materials during the evolution of the theatre have improved acoustics. The paper first briefly reviews evolution of the theatre in antiquity: following a systematic examination of acoustic simulation methods, the authors present acoustic simulations with six typical theatre forms, including early forms for which no previous acoustic analysis has been made. Refined simulations are then presented with a range of possible material characteristics. Based on the simulations, in the final section of the paper, the acoustic evolution is carried out through the SPL, reverberation time, and STI acoustic parameters. Scattering and diffraction from seat risers are significant in outdoor theatres, and these were examined in detail in a pilot room whereby a seat riser was considered as a panel and four mechanisms of diffraction and/or scattering from the panel were studied (Chourmouziadou, 2002; Chourmouziadou, Kang, 2006). An investigation into the effect of absorption and scattering coefficients on the sound fields is included, which makes comparisons with a wide range of absorption coefficients found in the literature for local materials. Various scattering/diffraction coefficients are also compared, including purely specular reflections, flat-panel scattering, and high-scattering coefficients.

In the same year, Farnetani *et al.* (2008) also published an analysis of the acoustic evolution from Greek to Roman theatres based on in-situ acoustic measurements in a group of five Greek and Roman ancient theatres, and on scale model measurements; however, the Epidaurus theatre is not included. Based on values of sound strength, the authors proposed that the sound energy is mainly present in the first part of the impulse response, which includes the direct sound and the two notable reflections from the floor and the stage (when present). In addition, there were early reflections that correspond to seven step edges behind the microphone position. The remaining dominating early energy could not be allocated to any particular part of the geometry. The wave theory of scattering from Declercq and Dekeyser (2007a) could not be correlated with their experimental results.

Finally, it should be borne in mind that Cocchi (2013) discusses the acoustics of ancient theatres from a historical perspective and examines the evidence for the relationship between acoustics and ancient theatre design.

3. Roman Theatres (150 BC – 400 AD)

The Roman theatre is commonly interpreted as the continuity of the taste for Greek performances, which Roman culture included in its leisure activities. The imperial era of Roman civilization witnessed not only the greatest upsurge in the construction of theatre, but also the export of the model from Rome to the provinces. In addition to being a symbol of Rome, the theatre must be recognized not only as an instrument of the new imperial ideology with its stage for ceremonies and acts with a high symbolic content, but also as a means for its political, religious, and propaganda content to be disseminated.

In fact, the Roman theatre identifies a whole series of transformations with respect to the old Greek-Hellenic structures according to this new conception and functionality.

The layout of the Roman and the late Hellenistic theatres followed the earlier Greek seating pattern, although they limited the seating arc to 180°. A stage-house was also added (*scaenae frons*) behind the actors, as was a raised acting area (*proscaenium*), a lower inclination of the tier, and awnings (*velaria*), which were hung overhead to shade the patrons. The chorus spoke from a hard-surfaced semi-circle (*orchestra*) in the centre of the audience.

The ground plan, section, and a photograph of the Roman theatre at Aspendus, Turkey, are shown in Fig. 4. This theatre is one of the best-preserved examples of the period. The greater technical expertise of the Roman engineers in comparison with that of the Greeks, due to their development of the arch, the vault, and the development of new materials such as the *opus caementicium*, would, in many cases, lead to a freer choice of the location of the building, thus allowing greater independence between the project and the topography of the city.

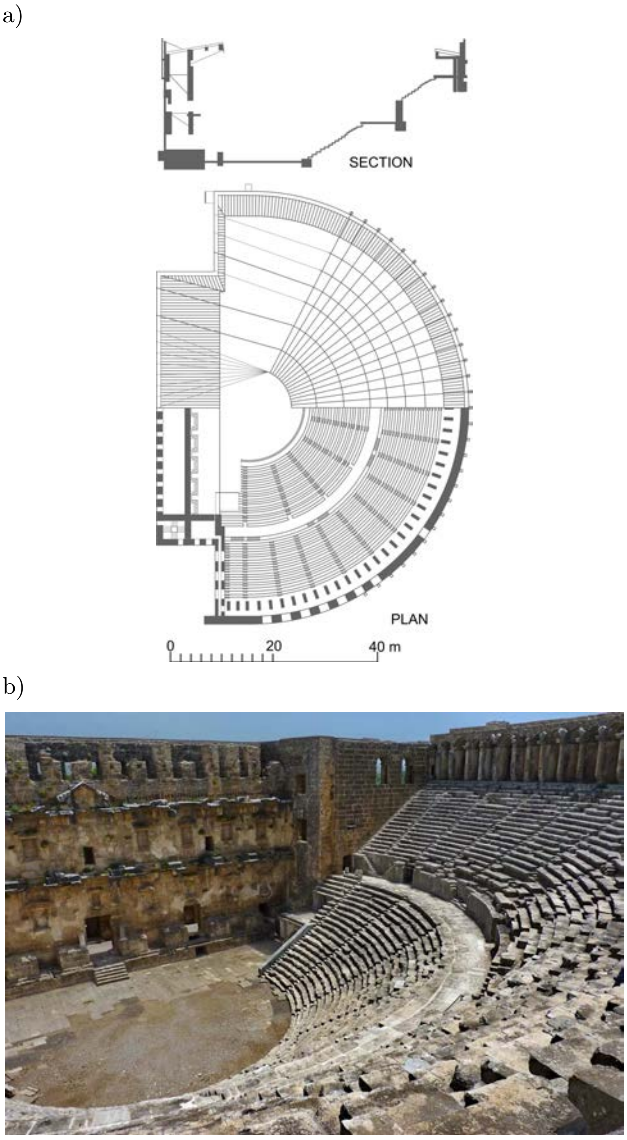

Fig. 4. The Roman theatre of Aspendus: a) ground plan and section; b) photograph of the venue (author: patano (CC BY-SA 3.0), source: https://commons.wikimedia.org/wiki/File:Aspendos_Theatre_-_panoramio.jpg).

The amphitheatre is a space related to gladiatorial combats, which were provided as entertainment, and had their origin in Italy, possibly from the Etruscian or Samnite culture. The main characteristics of amphitheatres are the oval-shaped 'Arena' in the middle and the audience seated on all sides around the arena. Like the theatre, it was an unroofed space with the possibility of a velum as sun protection. The most impressive of the Roman amphitheatres, the Flavian amphitheatre, was built between AD 70 and 81, and was later called the Colosseum, due to its proximity to a colossal statue of Nero. With a total seating capacity of about 40,000 people, it constitutes, except for racecourses, the largest structure for a seated audience of the ancient world; its architect remains unknown (Long, 2006; Izenour, 1996). The principles of the designs of Roman amphitheatres are used in modern stadia as a place for watching, whereby oral comprehension is not essential the acoustics of these performance spaces are therefore not reviewed here.

Much of our knowledge of Roman architecture comes from the writings of Vitruvius Pollio (Vitruvio, 1787), an architect of the time, who authored *De Architectura* (*Ten Books of Architecture*). Dating from around 27 BC, these books describe his concepts regarding many aspects of architecture, theatre design, and acoustics (fifth book). Several of his ideas were intuitive and practical, such as his warning about locating theatres with adequate ventilation (away from swamps and marshes), and that seating should not face south, since it would cause the audience to look directly into the sun. Unrestricted sightlines were considered particularly important, and he recommended that the edge of each row should fall on a straight line from the first to the last seat. His purpose was to assure good speech intelligibility as well as good sightlines that were free of obstacles. He also wrote that theatres should have large overturned amphora or sounding vases placed at regular intervals around the space to improve the acoustics. These were to be centred in cavities on small wedges that were 150 mm (6″) high such that the open mouth of the vase was exposed to the stage. The purpose of these vases remains unclear (see Sec. 5). Even Vitruvius could not cite an example of their use, although he does insist that they existed in the provinces (Long, 2006). He also carried out a classification of theatres according to their acoustics: dissonant (dry); circonsonant (reverberating); resonant (with echo); and consonant (sound amplification). Another prominent theoretical contribution in this regard is that of the work by Canac (1967), who studies various Roman geometries with the algorithm of image sources and shows how the first reflections in the *orchestra* and the back wall of the stage were important in the amplification of the voices of the actors, thereby supporting the direct sound.

Although the majority of Roman theatres are located in the Mediterranean area (Fig. 1 and Table 1), they were built in the main cities of the Roman Empire

(Mourjopoulos, Fausti, 2013) and have Greek origins. The decoration of the whole venue is luxurious, involving marble, columns, and inscriptions, especially on the stage, where all the designs of orders of the Roman architects are applied (Fig. 5).

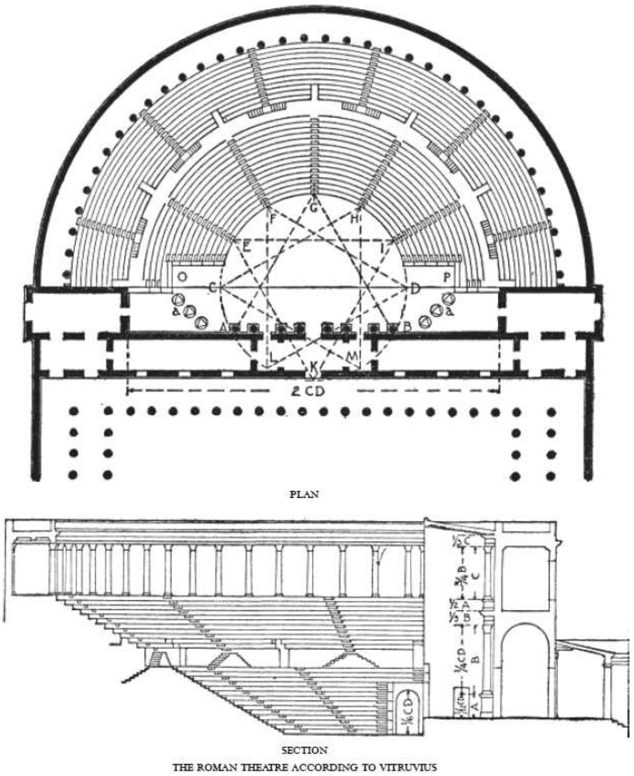

Fig. 5. Ground plan and section of a Roman Theatre according to Vitruvius (source: Project Gutenberg, http://www.gutenberg.org/files/20239/20239-h/20239-h.htm Parts of a Roman Theatre).

The structure of these theatres belongs either to a design built directly on the ground or to a design with a supporting structure. In general, these theatres were located in suitable areas so that a large part of the stands could be placed directly on the ground, that is, on the slopes of mountains or hills. The parts that could not benefit from this situation were structured with Roman concrete walls and vaulted corridors. The highest area of the stands, the *summa cavea*, tends to stand on an artificial structure.

The ways of designing the structure also varied. Initially, vaulted radial walls were constructed to form empty interior spaces. Circular galleries were later employed, which also served as corridors. Finally, a mixture of these two systems was introduced.

3.1. Parts of a Roman Theatre

In terms of its acoustic study, three well-defined areas can be established: the *scaena*, the *orchestra*, and the *cavea* (see Fig. 6, based on the reconstruction of Carthago Nova theatre in Cartagena, Spain).

The scaena: This contained the stage and all the elements and rooms necessary for the performances (Fig. 6). It was raised on a *podium* and could be divided into several parts, including the *proscaenium*, or space where actors performed on the *podium*. The part closest to the *orchestra*, and often somewhat higher, was called the *pulpitum*, whose surface tended to have a wooden cover. Under the *pulpitum*, there was the *hyposcaenium* or *hiposcaenium*, a hidden chamber for mechanisms and decorations. In the elevation of the *orchestra* stood a façade called *frons pulpiti*, whose design, over the centuries, took on several forms:

- Straight line, without *exedras* or niches and with the *frons pulpiti* either without decoration or with pilasters.
- Layout with central *exedra*, semi-circular in shape, with two other smaller rectangular entrances on its sides.
- Layout with three *exedras*, semi-circular in shape, interspersed with five rectangular intercalary entrances.

The *scaenae frons* was the name of the monumental wall that delimited the back of the *proscaenium* and, without doubt, presented the most spectacular element of the *scaena*. It consisted of one or several overlapping arrangements of orders with their columns and entablatures, crowned with a sloping roof with a double function: protection and acoustics. It contained three doors, a central or *valva regia*, and two lateral or *valva hospitalarium*. The *postscaenium* consisted of the group of dependencies located behind the *scaenae frons*: changing rooms, corridors, and dressing rooms. The *parascaenium* was made up of dependencies located on the sides of the *scaenae frons*, within which two doors, the *itinera versurarum*, communicated directly with the *proscaenium*. The *postscaenium porticus* was the exterior façade of the stage, with classical orders of blind arches, which sometimes formed a rear enclosure.

The orchestra: This was the semi-circular space (Fig. 6) located between the *scaena* and the *cavea*. In its Greek origin, in addition to being circular, it was the place where the choir that accompanied the performances was located. Its curved area was surrounded by several steps, *proedria*, reserved for the major personages of the city, such as solicitors, senators, and judges. It was acceded by great lateral vaulted corridors, *aditus*, along which certain spaces were located for special spectators called the *tribunal*. On its front, delimiting it along its straight zone, rose the *frons pulpiti*. In addition, the *orchestra* had access stairs to the *scaena*.

The cavea: This was the grandstand where the audience that attended the plays was accommodated (Fig. 6). Its general structure was divided into three horizontal zones (the *ima cavea*, the *media cavea*, and

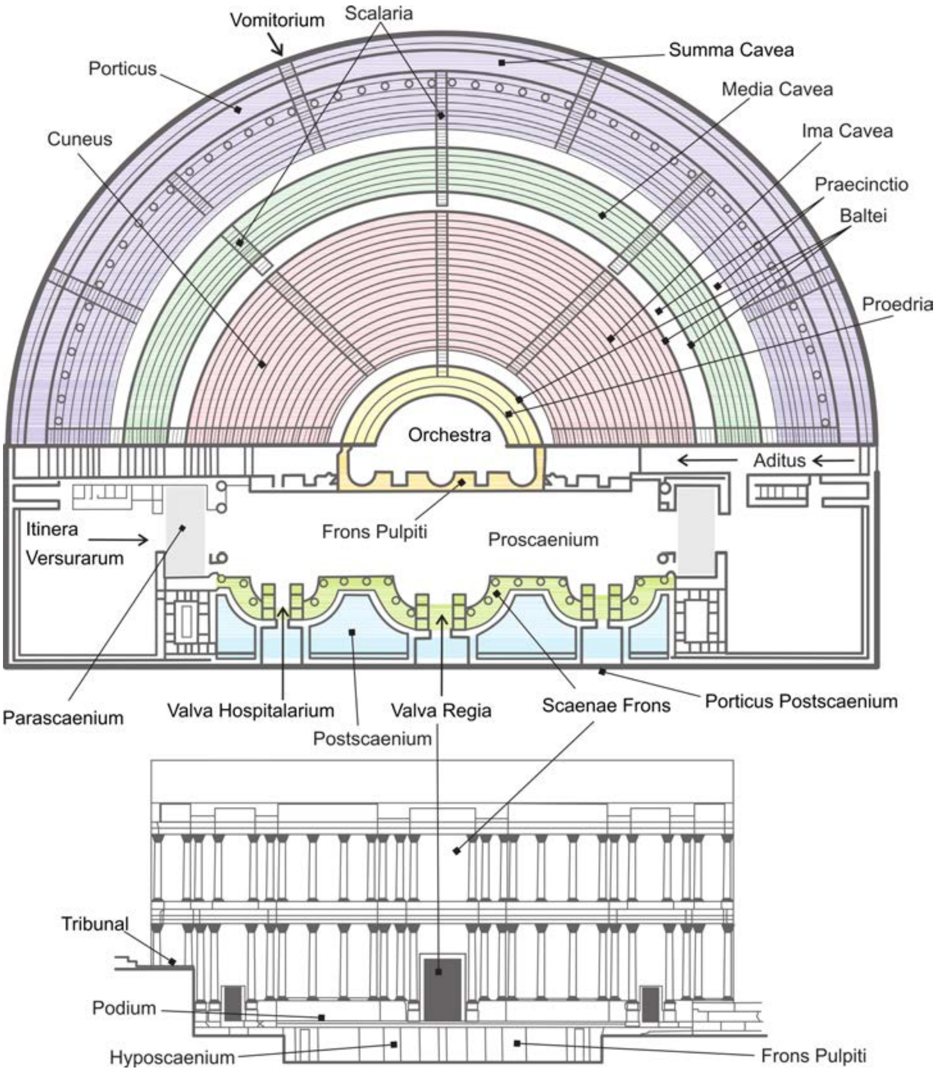

Fig. 6. General plan and elevation of the *scaneae frons* of a Roman theatre showing its main components.

the *summa cavea*), each of which was reserved for a certain class of spectator.

These areas used to be separated from each other by perimeter walls, 1.20 m in height, called *baltei*, which limited the horizontal corridors or *praecinctio* that connected the stairs and the doors. On the highest of the tiered areas, (either the *summa* or *media cavea*, depending on the case), porticoed corridors, (*porticus*) were constructed that led into the interior that was covered by the stands. Vertically, several parts can also be established.

These include the *scalaria* or stairs to access the different stands. These end in the corridors (*praecinctio*) which communicated with the *vomitorium* doors, and with entrance or exit corridors of the stands. The *cunei* or *cuneus*, were the wedge-shaped areas into which the stands were divided by the compartmentalization effect caused by the stairs.

The exterior of the theatre was directly related to the orography of the land upon which it was built: on whether the stands were supported by a slope or not. Whatever the case, the exterior was usually composed of a succession of classical orders of columns and arches on the first floor, and pilasters with blind arches on the upper floor, which were a reflection of the interior, both of the *cavea* and of the *scaenae frons*. Ancient Roman theatres have inspired much of today's open-air theatres; see for example the work by Sü and Yilmazer (2006).

3.2. Acoustics of Roman Theatres

Despite the importance of these theatres in Western culture and the long list of theatres built in the Imperial Era (see Table 1), the available acoustic information published in international forums remains scarce. For instance, in France, to the best of our knowledge, only the Theatre of Orange is mentioned geometrically, in a conference paper (Beckers, Borgia, 2009), which also describes the Theatre of Efesus in Turkey.

In the framework of the ERATO project, Rindel (2013) summarises the main goals of the project, and publishes the parameter values averaged across all source-receiver positions and over mid-frequencies of T_{30}, G, C_{80}, and STI, calculated in 2 different configurations (empty and fully occupied) of the theatres (Aspendus, Jerash south, and Syracuse) and odeons (Aosta and Aphrodisias). In order to study the possible existence of echoes, the room acoustics software, ODEON, was employed for the reconstruction (Gade *et al.*, 2005) of the Roman theatre in Aspendus (reflections called *circumsonant* by Vitruvius, 1787). The focus of reflections from the concave seating arrangement was clearly verified when the source was near to the centre of the stage and to a receiver position in the orchestra, but there were also reflections from the concave *praecinctio* via the canopy above the stage, and late reflections from the colonnade surrounding the theatre. The calculated impulse response in this position showed a clear echo with a delay of 125 ms. On the other hand, the idea of installing resonators in a theatre dates back to the times of Aristoxenus. Although these resonators could theoretically make sense as a measure against the focusing of sound from the concave shape of the stone seats in a theatre, the very small amount of absorption that can be obtained in practice makes it clear that the sounding vessels had no audible effect when installed in a theatre.

In the framework of the Italian research programme, PRIN 2005 "Resources for the acoustical and visual fruition, safeguard, and valorisation of ancient theatres", Guglielmetti *et al.* (2008) perform a thorough acoustic description of the spatial distribution of the sound field of the Roman theatre of ancient Ostia, from its origin (Agrippa, at the beginning of the 1st century BC) to the present day. The paper describes the on-site measurement survey carried out in the presence of a provisional stage and is in accordance with the standard specifications. These measurements are validated by means of acoustic simulation software (ODEON) and through comparison with other studies of Roman theatres. The study has been extended to include hypotheses of virtual restitutions of the theatre, over the centuries, based on historical data, records, and archaeological information. This has enabled a numerical simulation of the evolution of the acoustical properties of the theatre, which reveals that an increase of audience seating of the *cavea* has caused a detriment of the acoustic quality, particularly that of intelligibility. Furthermore, the authors have analysed the effect of cultural development on performance through auralisation: in its current state, the theatre is suitable for spoken performances while the ancient structures were more appropriate for drama and music.

Regarding the Roman Theatre of Posillipo in Naples, Iannace and Berardi (2017) published on-site measurements of the current state and acoustic reconstruction of the *scaena* and the *cavea* as presented in Roman times, while Sato *et al.* (2002) studied the Roman Theatre at Taormina in Italy: this theatre has a partially remaining stage construction behind the orchestra. The effect of the stage construction on the sound field was determined in terms of the temporal and spatial factors of the sound field. It was found that the stage construction affects the magnitude of the inter-aural cross correlation coefficient (IACC).

The study by Iannace and Trematerra (2014) presents the acoustic history of the Beneventum Roman theatre, from the time of its construction in the Roman period to the present day. The theatre, built in the 2nd century AD, was later abandoned. According to Iannace and Trematerra, the building materials of the theatre were then used during the Langobardic Age for the construction of defensive walls and for the adornment of churches and buildings. Furthermore, in the following centuries, several houses were built on the site of the old theatre. At the beginning of the 1900s, the houses were demolished, the buried parts of the theatre were brought to light, and the structures of the theatre were strengthened. The recovery work was completed in 1950. The theatre today is not only an ancient monument, but also the centre of major social activities with national and international festivals of music, dancing, and drama. Using specific software for acoustic simulation (ODEON), and with a 3D virtual model of the theatre, the authors estimated the acoustic properties for the Imperial Age. With acoustic measurements carried out in situ, the acoustic properties were also evaluated in the current state of the theatre: the average reverberation time (T_{30}) measured (without audience) was 0.80 s, while the EDT was low for the absence of sound reflection of the *scaena* wall, which presented a significant reflecting surface. Moreover, an increase was found in the reverberation time at the frequency of 500 Hz due to the reflections of the sound waves on the seating rows which, thanks to their dimensions (0.40 m high and 0.70 m deep), improved the sound amplification (Declercq, Dekeyser, 2007a). The reverberation time calculated for the virtual model of the Roman period had a value greater than the reverberation time value measured in the current state, with a difference of about 1.0 s. The seating rows were originally made of marble, now in porous brick, and are currently less significant as reflective surfaces than the *scaena* wall and the *summa cavea.* The parameter C_{80} is too high for a good reception of music, while D_{50} reaches a good value for the intelligibility of speech. The excellent average values of STI (0.81 when the sound source was on the *scaena*, and 0.84 when the sound source was in the *orchestra*) confirm a high value for the direct-sound components. The theatre in its current state is suitable for speech comprehension; in fact, speech intelligibility is excellent throughout the large audience area. In view of these results, the authors conclude that, for a better sound perception by the listeners, with actors and singers singing and speaking live, the actors should act in the orchestra and not on the *scaena*, as happens today.

In the early Imperial Age, open-air Roman theatres and amphiteatres were endowed with *velaria*. *Velaria* were awnings made of sailcloth, in canvas, linen, or cotton, attached to spokes that could be extended or retracted with ropes and pulleys over the *cavea* (Alfano *et al.*, 2015). Their main purpose was to provide shade for spectators who attended the spectacle in the blistering sun and heat. In order to understand whether *velaria* can affect the acoustics of the theatres, Alfano *et al.* (2015) perform acoustic measurements in two theatres of southern Italy in the Campania region: the large theatre of Pompeii, built in around the 2nd century BC, which was initially a Greek-style construction that was later enlarged and restored extensively during the Augustan period; and the Roman theatre of Benevento, which was built during the Trajanian period 98-117 AD and opened in 126 AD under the Emperor Hadrian. The paper presents a brief overview of the awnings in ancient Roman theatres based on the provisions for mounting awnings found in the remains of Roman theatres and amphitheatres and depicted in certain frescoes and murals.

Measurements of impulse responses in the two theatres were carried out with the explosion of balloons in the former and with a dodecahedron source in the latter. Once the T_{30} parameters were attained, the 3D acoustic models implemented in the theatres for acoustic simulation with the ODEON software could be validated. The calibrated models of the two theatres enable the results of T_{30} and EDT to be ascertained for four values of the surface density of the materials that constitute the awnings (0.5, 1.0, 1.5, and 2.0 kg/m^2) and their comparison to be performed with the results of the acoustic parameters in the theatre without awnings.

Results in terms of receiver-averaged descriptors of the reverberation EDT and T_{30} show an average increment of the parameters with the increment of the surface density. In the case of the large theatre of Pompeii, the spectral behaviour of EDT and T_{30} resembles the expected behaviour of similarly dimensioned tents and rooms with a high percentage of thin glass walls. In the Roman theatre of Benevento, the initial peak at 500 Hz without awnings is increasingly amplified in tune with the density, and is related to the scattering caused by the periodicity of the seat rows in the *cavea*, as described by Declerq and Dekeyser (2007a). Since *velaria* of antiquity must have had a density of 0.5 kg/m^2, the supposed constitution and weight of *velaria* over the *cavea* in those times could not have drastically changed their acoustics. However, in modern performances, suitable awnings that combine the mass-per-unit surface of the material of the awnings and the location can together improve the natural acoustics of the spaces.

Iannace *et al.* (2013) report on the acoustic evolution of the large theatre of Pompeii, spanning from the Greek-Hellenistic and Roman period up to the present day. Initially, the style of the theatre was Greek-Hellenistic of an elongated U shape and a *cavea* built into the top of a hill. During the Roman period, the shape of the theatre was changed to have a larger stage and a *summa cavea* was added to accommodate approximately 5,000 spectators. After having been recovered from under the Vesuvius lava, it was partially reconstructed. More recently, the original *cavea* covered with grass and soil has been paved with bricks and hence the theatre can now provide a space for a variety of modern performances. Its acoustic characteristics have been analysed using a virtual model for the Greek-Hellenistic period, the refurbishments of the Roman period, and again for the later configurations when the *cavea* was grass-covered and then paved with bricks, by means of the acoustic parameters calculated in the simulations (T_{30}, EDT, C_{80}, and D_{50}, spatially averaged versus frequency). The acoustic evolution for the various configurations of the theatre has been studied through computer simulations with a virtual model using the ODEON software based on geometrical acoustics. The results obtained are in accordance with simulations and measurements *in situ* for theatres built in the same historical periods and are comparable with the results of other authors. Their analysis concludes that the theatre, in its present configuration, has inadequate acoustics for musical purposes due to its low reverberation time and to the fact that its C_{80} value exceeds the optimum for symphony and classical concerts ($-2\text{ dB} < C_{80} < 2\text{ dB}$) (Barron, 1993). Furthermore, all the assessments were carried out without an audience, and the presence of an audience is expected to change the acoustic properties of the theatre (the values of T_{30} decreasing and C_{80} increasing). In the authors' words, the acoustic perception of the public depends not only on "what they hear", but also on "what they see", and in this regard the Pompeii large theatre is a spectacular space where optics, acoustics, performance, and historical value all come together.

In Hispania, Spain, 22 structures of this type remain, several of which are in an excellent state of conservation, such as the Roman theatre of Emerita Augusta (Merida). In southern Spain, there is also special interest for the conservation and reuse of these historic buildings, of which the International Forum of Roman Theatres (held in Seville), in its four editions stands as a clear example (The IV International Forum of Roman Theatres, 2018). This Forum is an open space for the study and discussion of classical theatres from the point of view of all the agents involved: researchers (historians); excavators (archaeologists); rehabilitators (architects and technicians); artists (writers, designers, choreographers, and producers); and especially the Public, to which all this work is addressed, whether as a visitor or a spectator.

In relation to published papers, the measurements and acoustic simulation carried out with CATT-Acoustic software of the Italica theatre (located in Santiponce, Seville) (Álvarez-Corbacho *et al.*, 2014) have only been published in English. This theatre has also been studied from the point of view of the efficiency of constructive restoration in heritage (Gómez-de-Cózar *et al.*, 2019), as have the acoustic measurements and virtual reconstruction of the theatre of Regina Turdulorum (Casas de Reina, Badajoz) (Álvarez-Corbacho *et al.*, 2015) and the virtual reconstruction of the Roman theatre of Cadiz (Álvarez-Corbacho *et al.*, 2018). Regarding the latter theatre, its construction date and its 120-metre diameter make it the oldest and the second-largest Roman theatre in the Iberian Peninsula, with an estimated capacity of more than 10,000 spectators. The section of the gallery (Fig. 7), through which the viewers accessed the *cavea*, is in an optimal condition of conservation, whereby the barrel vault that covers it, the oyster stone rigging of the interior wall, the skylights that provided natural light, and the *vomitoria* that communicated directly with the *cavea* all deserve mention. An acoustic survey has also been carried out in Segobriga theatre in Saelices, Cuenca (Álvarez-Corbacho *et al.*, 2019). Furthermore, based on photogrammetry, the authors have made acoustic restitution of the Roman theatre of Palmyra, Syria (Fig. 8) (Álvarez-Corbacho *et al.*, 2017).

Fig. 7. Image of the gallery, through which viewers accessed the *cavea* in the Roman theatre of Cadiz (author: A. Álvarez-Corbacho).

The authors of this work are involved in a national research project that aims to study and revalue the acoustics of the Roman theatres of Spain, and consequently, due to this interest, the Roman theatres of the world are indicated in Table 1 of Appendix. However, due to lack of space, a photograph of each venue has not been presented. The list that follows is in alphabetical order of the countries, whereby a total of 198 theatres appear together with their geographical coordinates, the diameter of the *cavea*, and the references of acoustic pieces of research carried out therein. For any additional architectural information on these enclosures, the reader is referred to the magnificent work by Sear (2006).

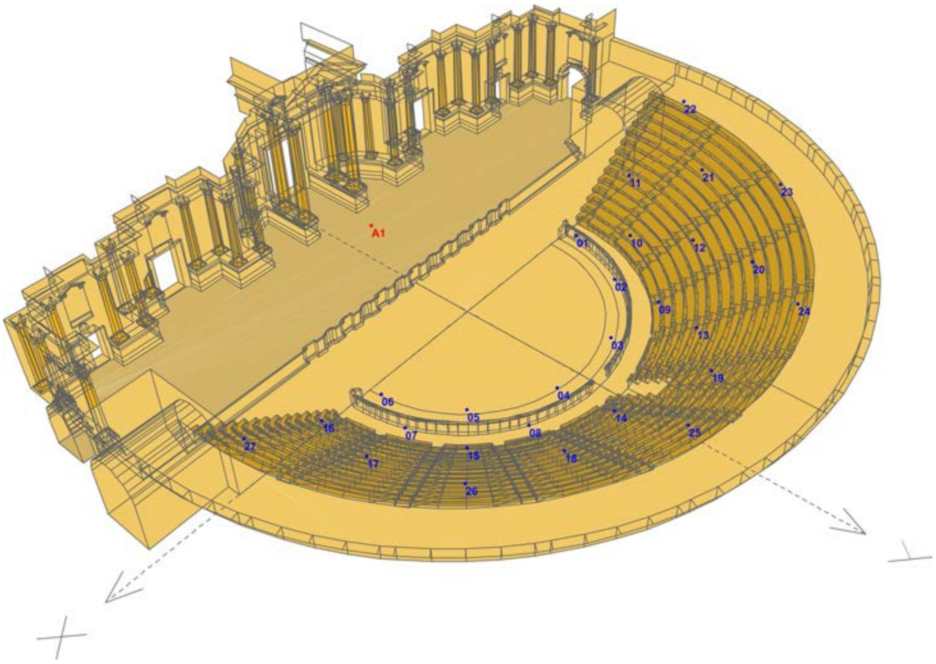

Fig. 8. 3D acoustic model of the Roman theatre of Palmyra, Syria.

It is pertinent to point out here that, although the acoustic characteristics of these spaces have been studied through the standard acoustic parameters for closed spaces from the ISO 3382-1, many doubts have recently arisen regarding the validity of using this metrology for these open-air spaces. In this regard, Farnetani *et al.* (2008) have already pointed out the weakness of the EDT parameter for the qualification of the acoustic quality of these enclosures, due to its great variability in source-receiver position. Furthermore, Mo and Wang (2013), by means of a geometrical acoustics simulation programme, model an unroofed space and an enclosed space with approximately the same exponential decay and examine the difference in perceived reverberation. Synthetic listening signals were generated by convolving the simulated impulse responses in both spaces with the anechoic music signals. Experiments on subjective dissimilarity judgments concerning reverberation show that the perceived reverberance in the unroofed space is not only affected by the temporal characteristics during the decay process, but also by the spatial characteristics of the reflections. Therefore, the authors highlight that the conventional reverberation parameters described in ISO 3382, which are measured by a monophonic system solely on the rate of sound energy decay, are unsuitable for the evaluation of the subjective reverberation of an unroofed space, such as those ancient spaces of performance.

4. Odea: from indoor to outdoor theatres

The odeon (Greek *ωδεον*, Latin *odeum*, plural *odea* and paraphrased as odeon) was also originally a Greek-type building used for song and music. It was a roofed, columned hall, where the columns disturbed sightlines, such as the odeon of Pericles in Athens, built 446–442 BC. These smaller venues might have emerged due to the change in the dramatic styles: late comedies by Greek playwrights Sophocles and Euripides depended less on the chorus and more on the dialogue between actors (Long, 2006). In the 1st century BC, the Romans developed the odeon into a roofed theatre without columns and with the audience seated in a semi-circular arrangement similar to that of the theatre (Izenour, 1992). It is characteristic for the odeon that the building has very thick walls that could support the roof, and the shape is either rectangular or semi-circular: the latter presenting a considerable challenge to structural engineering. Few remain, perhaps due to their wooden roof construction.

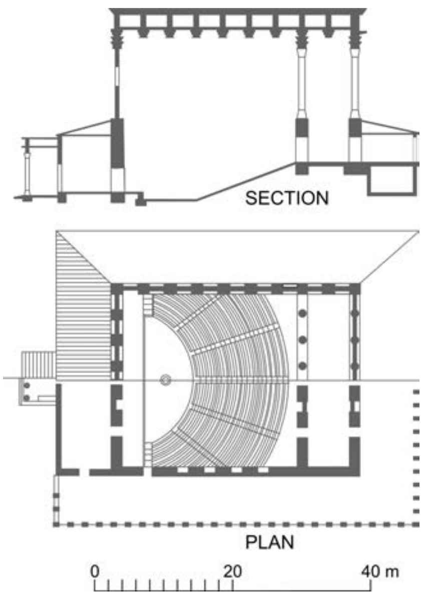

Fig. 9. Longitudianal section and ground plan of the odeon of Agrippa in Athens, Greece.

For instance, the odeon of Agrippa, a structure built in Athens in Roman times (12 BC), was a remarkable building. Shown in Fig. 9, it had a clear wood-trussed span of over 25 metres. It finally collapsed in the middle of the 2nd century. These structures, which ranged in size from 200 to 1,500 seats, are found in many ancient Greek cities (Izenour, 1992). According to archaeologists, the roofed section of such theatres was constructed from cedar wood and had a semi-circular shape, partially covering the marble *koilon*. In several cases, an elaborate timber roof covered the whole seating area and the orchestra. The partially-roofed design along with the perimetrically-located windows allowed natural lighting to reach the stage. The design for the *odea* evolved from earlier and larger open-air theatres although it remains unclear whether the roof was added in order to protect the audience or whether it was built in order to improve the acoustics for music performances.

In all existing *odea*, such roofed timber structures either have collapsed or have been burned over the centuries, and hence these buildings are currently preserved as open-air theatres. For this reason, the specialised function of the *odea* as buildings for music performances is largely unknown or misunderstood, and are nowadays considered as open-air ancient theatres.

Due to these circumstances, the most general methodology followed for the acoustic study of these spaces involves performing acoustic measurements in the current outdoor configuration. The agreement between the measured and simulated acoustic parameters in the outdoor version of the odeon makes it possible to validate the virtual acoustic model that would include the roof (based on historical documentation) and to simulate the acoustic conditions within this historical model.

Such is the case of the odeon of Herod Atticus, built on the southern slope of Athens acropolis in 161 AD by Tiberius Claudius Atticus Herodes. The *odeum* was burnt down in 267 AD, but, in 1950, work began to restore it to its current open-air form, and today it is used every summer largely for music performances during the Athens Festival. Constructed in marble, it has a capacity of nearly 5,000 spectators. Vassilantonopoulos and Mourjopoulos (2009) conclude that the building behaves acoustically in a completely different way: the measured open-air odeon has "dry" acoustics, which are typical of a semi-open space, whereby the equivalent reverberation time is in the order of 0.5 s and the speech intelligibility is very good, even at the furthest listening positions. The simulated roofed odeon presents an enclosed space of 9,750 m^3 with an appropriate reverberation time of 2.2 s, although speech intelligibility was poor, especially for the most distant listening positions. The increase in late reflection energy generated by multipath reflections arriving from the roof after 200 ms together with the acoustic strength criterion support the acoustic reproduction of musical instruments and vocal performances for most listening positions. Such significant differences in acoustics and function between these spaces may lead to the assumption that the roofed sections were added in order to facilitate their use for music performances.

With similar approaches, Berardi *el al.* (2016) acoustically characterize the small theatre known as the Theatrum Tectum or Odeon of Pompeii (in southern Italy) that today is an open-air theatre, but that was, during the Roman period, partially or completely roofed. By means of acoustic simulation with ODEON software, these authors reconstruct the version of the theatre with a roof with archaeological considerations. They compare the acoustic parameters in their spectral behaviour (spatially averaged), depending on the receiver-source distance, and through maps; the acoustics of these enclosures are ratified as appropriate for the reproduction of musical instruments and singing voices.

Fig. 10. The Roman odeon of Patras, Greece (Photograph by Carole Raddato (CC BY-SA 2.0), source: https://commons.wikimedia.org/wiki/File:The_recently_restored_Roman_Odeon_of_Ancient_Patrai,_built_before_160_AD,_Patras,_Greece_(14037786339).jpg).

In this section, the acoustics of Patras's Odeon, Greece (Fig. 10) is also studied: this is a well-preserved open-air ancient Roman theatre that has been investigated via computer model simulation and an innovative set of acoustic measurements (Vassilantonopoulos *et al.*, 2005). These tests were aimed at verifying the accuracy of the modelling procedure, optimising its parameters, and investigating the various means for describing the 3D sound field for acoustic analysis and auralisation (by using CATT-Acoustic). The detailed computer simulation of the theatre and acoustic measurements were made for 5 identical listener/receiver positions, respectively. The measurements consisted of single-channel impulse responses, 8-channel microphone array responses, and 2-channel binaural responses. From the analysis of the single-channel response measurements and the simulation results, comparisons were drawn related to various acoustic parameters (RASTI, D_{50}, C_{80}). The microphone array responses were processed to generate detailed spatial results for the theatre sound field. Finally, the binaural response measurements were employed for comparisons via psychoacoustical tests between computer simulation-generated auralisations and binaural audio signals. The authors concluded that the theatre simulations showed an acceptable degree of similarity to the measured results. Nevertheless, certain acoustic parameters were underestimated by the model, probably due to the simplified simulation of diffusion, which appears to play a significant role in the soundfield of the open-air ancient theatre. Auralisations from the model and measurements were easily distinguished by listeners, but this may be partly attributed to a mismatch between the head-related transfer function, in addition to the imperfect description of the absorption and diffusion of the model surfaces. The significance of the extraction of directional information from measured and simulated responses was also confirmed, which enabled a better interpretation of time, frequency, and directional soundfield information in such theatres (Vassilantonopoulos *et al.*, 2005).

Two innovative methods for measurement and analysis of 3D impulse responses in theatres provided a spatial resolution significantly better than that obtainable with previously existing technology (sum-and-delay beamforming for massive microphone arrays, 1st-order Ambisonics for B-format microphones). Furthermore, these new methods produce easy-to-understand graphical animations of the spatial-temporal information. These methods have been applied to this Roman odeon in Patras by Farina and Tronchin (2013).

Other pieces of research on odeons belonging to the ERATO project correspond to a case study where the authors create an interactive real-time scenario of a virtual audience in the ancient Roman odeon in

Aphrodisias, Turkey (De Heras-Ciechomski *et al.*, 2004). Based on historical sources, the building, music, and the auralisation of crowd sound (Rindel *et al.*, 2006) are reconstructed and several techniques are described that achieve high visual quality for a large number of virtual humans involving a complex architectural model while still maintaining interactive frame rates. These authors propose a comprehensive framework for the creation of crowd scenarios. Furthermore, the odeon of Aosta, Italy, is selected in this project (Rindel, 2013) since it is the only known example where several of the outer walls still exist at full height, and since its outer walls follow a rectangular shape similar to that of the missing odeon of Agrippa in Athens.

Although acoustic measurements in classical, Greek, Roman and Odeon theatres have largely been carried out according to standardised empirical procedures (ISO 3382-1, 2009) for enclosures, the analysis of the results remains highly variable, thereby rendering difficulties in their comparison: several authors use the point-to-point analysis either averaged across all octave bands, or at medium frequencies; other authors give a unique value of the parameters in the theatre; others study the behaviour of the parameters as a function of source-receiver distance and angle from the source at mid frequencies; sometimes the position of the sound source remains unspecified; other papers use two positions of the sound source and up to 5 positions of the sound source. Furthermore, in other pieces of research, only reverberation time measurements are performed, for the calibration of the acoustic simulation model in the current state.

Despite this inconvenience, the authors have extracted information common to several pieces of research, and, in Fig. 11, present the results of the reverberation time T_{30}, the definition D_{50}, and the clarity C_{80} in octave bands, together with the results of the sound strength G_{mid}, as a function of source-receiver distance, and its dependence on a free field in Fig. 12. The references used for the construction of the plotted graphs are indicated in the captions. Due to the lack of uniformity in the study of the acoustic parameters, the quantity of data available varies for the different acoustic parameters.

From the figures shown, only a highly qualitative analysis can be deserved: for the reverberation time T_{30}, the behaviour with frequency is highly dependent on the theatre although, in the majority, except for certain exceptions, the behaviour is very flat: greater dependence on frequency and on the theatre in question is obtained for the clarity and definition parameters. It should also be noted that Greek theatres and the odeon constitute the spaces in the shortest range of reverberation times, the greatest values of definition, and the greatest excess of clarity. However, in terms of sound amplification, higher values of the sound strength parameter are obtained for the Roman theatres than for the Greek theatres and the amplification is of several decibels in both cases with respect to free field conditions.

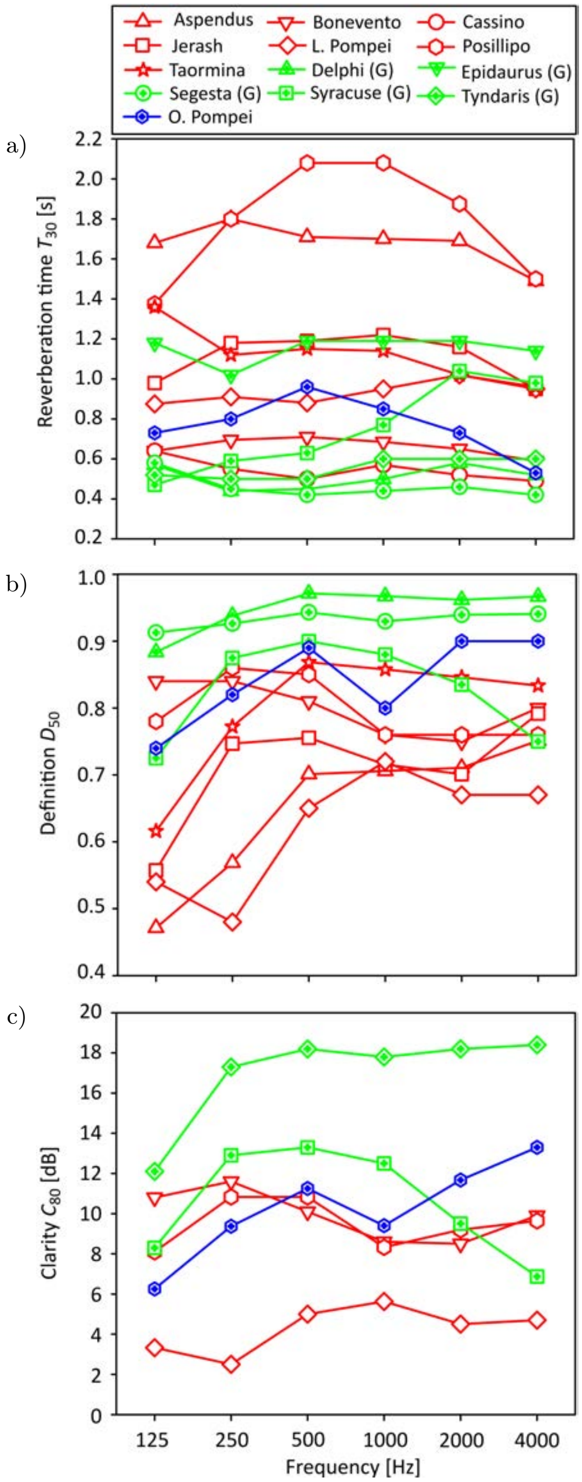

Fig. 11. a) T_{30}, b) D_{50}, and c) C_{80} parameters for various ancient theatres as a function of frequency. Data is extracted from (Berardi *et al.*, 2016; Bo *et al.*, 2016; Farnetani *et al.*, 2008; Gade, Angelakis, 2006; Gullo *et al.*, 2008; Iannace, Berardi, 2017; Iannace, Trematerra, 2014; Vassilantonopoulos *et al.*, 2011).

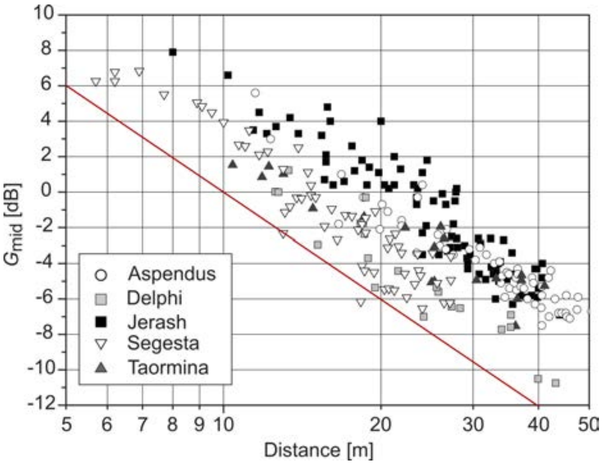

Fig. 12. G_{mid} as a function of source-receiver distance. Data from (Farnetani et al., 2008). The line of the free field is also shown.

5. Singular acoustic elements in Ancient theatres

Due to the fact that most ancient theatres were built with highly reflective materials, they possibly used certain items to modify their acoustics, such as actors' masks, vessels, and vases.

Regarding the properties of sounding vessels, there have been the most varied hypotheses: Knudsen (1932) considers them as sound absorbers while others believe that these vessels were used for amplification or for improvement in sound quality (Zakinthinos, Skarlatos, 2007).

In order to shed light onto this issue, Polychronopoulos *et al.* (2013) perform an acoustic simulation of the Lyttus Theatre, in Crete, since there was evidence that this theatre employed such vessels. A 3-dimensional CAD model with 39 acoustic vases was designed and, in accordance with the information available, the authors proposed dimensions for the resonator, such as a resonant frequency of approximately 273 Hz (obtained by using the Finite Element Method model). Two acoustic models of the theatre were created, with and without vessels, for the application of software based on the ray-tracing method (CATT-Acoustic), in both cases without the public present.

From the comparison of the two situations of the theatre, the main effect of the resonators falls on the centre time parameter. For all positions, the centre time is greater when near the resonators, and it decreases when distanced from these vessels. Without the presence of the resonators, the centre time remains almost constant; therefore, the resonators appear to increase this parameter for positions nearby in the theatre, and this increase is stronger for their near-field area. The overall effect of resonators on sound amplification was found to be minimal in comparison with the level of produced sound pressure. Certain effects were observed for the J_{LF} index, with high values for close proximity to the resonators, but this effect gradually decreased with increasing distance. From these simulations, it appears that the effect of resonators both on centre time and on early lateral energy fraction is significant and it can be deduced that the cavity-resonator modules were probably employed to provide a form of artificial reverberation for positions nearby in the ancient theatres. Their effect on other indices was found to be rather poor compared with the effect of the main source on the stage. This overly subtle acoustic effect could be the reason for their abandonment in subsequent theatres.

Another interesting topic related to the acoustics of the ancient theatres involves the connection that exists between the bronze vessels of the Greek theatres and the ceramic vessels found in the Ancient and Medieval churches.

As described in the magnificent work by Valière *et al.* (2013), during the Middle Ages and later times, the practice of using acoustical pots in churches spread throughout European architecture. The interest for their origin emerged during the era in which the pots were discovered inside walls and vaults of medieval churches (19th century). The scholars connected these pots with the ancient acoustic devices, *echea*, which Vitruvius (1787) points out in his description of Greek theatres.

However, as described by the authors, at least three differences can be noted between the *echea* of the Greek theatres and the acoustic pots placed in medieval churches. The first is that Greek theatres are open-air spaces, where an amplification of the sound is desirable and where reverberation is poor. Conversely, medieval churches are enclosures and the propagation of sound is governed by energy decay and reverberation.

Another major difference is that bronze vases were placed in niches so that they could freely vibrate inside their stone housing. The medieval acoustic pots, however, were inserted within the vaults and walls embedded inside masonry, and therefore they could not vibrate freely. For the former devices, their acoustic behaviour is based on structural vibration, while for the latter it is based on the volume of the air included in the pots. The third question is related to the number of devices inserted in the buildings: whilst the number of bronze vases in the theatres is precisely determined according to Vitruvius's text, the number of pots inserted inside the walls and the vaults of the churches varies greatly.

Despite these physical differences, from an attentive literary analysis and from the text of Vitruvius, the authors reach two major conclusions regarding these devices. First, that earthen pots were inserted into the walls of certain buildings (theatres and temples) in the 1st century BC. Secondly, Vitruvius's writings (his manuscript *De Architectura* was widely available and its reading was recommended in many medieval monastic libraries) regarding acoustics probably influenced the architects and builders in the Middle Ages, and later, influenced the introduction of these acoustic devices either during or following the construction of the churches.

Analysis of historical texts by VALIÈRE *et al.* (2013) shows the acoustical intention of the church builders with the insertion of the pots, although no indications as to how the pots would modify the acoustics can be found.

In this regard, several experiments conclude that a noticeable amplification occurred, while other studies carried out on Swiss Orthodox churches show a weak acoustic effect at low frequencies (DESARNAULDS *et al.*, 2001). Another study implies that no clear differences were detectable (MIJIĆ, ŜUMARAC-PAVLOVIĆ, 2004), while others concluded that a reduction of reverberation was slightly perceptible (ZAKINTHINOS, SKARLATOS, 2007; CARVALHO *et al.*, 2002). These latter experiments involved a large number of modern ceramic pots placed on the floor: CARVALHO *et al.* (2002) employed 30 pots in a reverberant chamber, and ZAKINTHINOS and SKARLATOS (2007) used 300 pots in a church.

It should also be mentioned here that BARBA *et al.* (2008) have verified that the distribution of the bronze vessels in the *cavea* of the Roman theatres (as stated by Vitruvius) is in accordance with the Greek tetrachordal musical system developed by Aristoxenus.

In another aspect, TSILFIDIS *et al.* (2013) study the acoustic properties and functionality of the masks used in the Greek theatre, for which a generic mask template was used. Given that archaeological excavations failed to reveal any ancient theatre mask template, several mask prototypes were constructed, whose exact form, shape and material was deduced from the limited archaeological data available. The first part of the work presents the theatrical function of the masks and the historical background, a discussion of form and features of the masks, and their construction. The generic prototypes (5) were measured using a KEMAR dummy head, under free field conditions with low background noise, and not in an ancient theatre; the signal emitted (sweep signals, frequency 100–20,000 Hz, and duration 15 s) was transmitted through the mouth of the simulator and recorded at a distance of 1 m at the same height as that of the mannequin-mask and in-ear microphones for the binaural measurements. Measurements were taken both for the mannequin with and without the mask and for the recorded responses to the excitation signal at different azimuth angles.

Comparisons of the frequency responses of all measured masks at each azimuth angle enabled the authors to obtain a mean value of the five prototypes. The mean data from the 5 different mask template types and from all azimuth measurements (from 0–180° in steps of 30°) were used in order to extrapolate the mean mask polar pattern, for various frequency bands.

The polar diagram shows that the masks enhance the source off-axis (180°) gain for all frequencies, except for the 2 kHz octave band where the mask fails to significantly change the actor's voice. The frequency responses of these mean values were then compared with the frequency responses without the mask. It appears that the combined actor and mask response is dominated by the speaker's directivity and is only mildly affected by the filter effect of the mask. The self-perception of actors wearing the masks is assessed in a simplified way; it takes into account only the transmitted acoustic path from the mouth simulator to each ear entrance, and hence examines no other complex mechanisms, such as bone conduction. The mask significantly amplifies the speech signal levels that reach the mannequin's ears, even for mask templates with the ears left open. The boost on the level is, on average, 18 dB and the effect is greater for high frequencies. This effect may explain the difficulty of contemporary mask-wearing theatre actors to perform with such theatrical masks without proper training and lengthy adaptation. It is evident that actors in times of old should have been highly trained to adapt their voice delivery and sustain such increased sound levels in their own ears, over the duration of ancient drama performances. It should be noted that, in order to ensure proper intelligibility over theatre audience distances of up to 60 m, levels of at least 90 dBA should be produced by the actors, which indicates that with masks, the potential in-ear levels could be up to 110 dBA. This points towards the possibility that the actors wore some kind of earplugs for the protection of their hearing from prospective damage and to ensure listening comfort during the performance. In fact, in accordance with the authors' experience, earplugs are often employed during many modern theatre performances in which the actors are masked.

6. Use of Ancient Theatres for contemporary performances

Certain authors emphasize the re-use of these classical theatres for contemporary musical and artistic events if the theatres are well preserved or restored. In this regard, in the work by PRODI *et al.* (2013), the authors attune the natural acoustics of the ancient theatre of Syracuse, Sicily, with a 1:20 scale model of the theatre. A reference set-up of the scale model was fixed; which presented the widest cavea (diameter 143 m) without any additional elements (such as the stage building and the gallery in the upper part). This "bare" condition is representative of many ancient theatres still in use and is not optimized for the acoustics in a large part of the audience. The aim of the work, through the analysis of acoustical measurement in this scale model (complying with ISO 3382-1, for closed spaces), is the analysis of the results of reverberation (T_{30}), sound strength (G), and clarity (C_{80}) for three stage sets in order to provide the impulse response with useful early reflections which could subsequently be integrated into the direct sound via the Haas effect. The three stage sets consisted of: an orchestra shell; eight reflective screens (2 m long and 3 m high) arranged in a trapezoidal shape; and 8 smaller modules (1 m long and 3 m high).

In the light of their results, it was concluded that the lack of extended reflective surfaces in the stage area, which is quite common in ancient theatres due to their state of conservation, can be compensated for by adding a few architectural elements to support the sound propagation and to improve the listening conditions. An attempt was made in this work in this direction in that the possible benefits and the limits of passive strategies in the adaptation of acoustics to modern performances were investigated.

Although the scale modelling could not cover a sufficient number of configurations necessary for a comprehensive analysis, several guidelines can be proposed for the acousticians dealing with similar issues. Within natural acoustics, a few large reflecting panels arranged on the stage to delimit the performance area can provide a better compromise than smaller panels and even than an orchestra shell. In fact, these elements are able to compensate partially for excess clarity, and to increase the sound level to a certain extent with better performance in the farthest positions. The orchestra shell provides better (i.e., lower) clarity but also provides a lower sound level in the distant locations. However, the reverberation time cannot be corrected effectively with these simple means.

Other pieces of research combine studies of acoustic and luminous comfort of these ancient theatres, for example Bo *et al.* (2015) present a parametric study of the same Greek theatre of Syracuse through the prediction software tools ODEON and Relus, by further adding various scenic elements in the theatre in order to evaluate their influence in acoustic quality and solar radiation. By focusing on the acoustic aspect based on measurements of background noise and reverberation times in the venue, and in accordance with ISO 3382-1 requirements, the virtual model was adjusted to recreate a model to explore differences in acoustic conditions through the smart design of various elements of the scenery, particularly the scenic front, stage floor, and back panels. To assess the acoustics of the theatre, the calculated values of the sound strength and clarity have been used as room acoustic criteria. The implementation of these stage designs enables the reinforcement of sound propagation, since the sound strength parameter, which is associated to the amplification of sound, is greatly improved with the addition of the scenic front, and increased by about 4 dB in the furthest positions from the source compared to the empty theatre, with all the elements of the stage. Furthermore, the study presents a methodology for the approach of visual comfort of the audience in an open-air theatre.

Since ancient theatres are used in the modern age for various cultural activities especially in the summer season, the audience often criticises the poor acoustics of the theatres; an influential acoustic aspect is the presence of the audience itself in the *cavea*. This aspect is difficult to carry out via in-situ measurements, and for this reason Iannace and Trematerra (2018) use numerical simulations to assess this influence. Through the analyses of EDT, T_{30}, C_{80}, and D_{50} parameters, they consider the acoustics of four theatres in Italy: the two Roman theatres of Cassino and Benevento, and the two Greco-Roman theatres of Taormina and the large theatre of Pompeii. The analysis of the numerical simulations shows that the influence of the audience on the acoustics of theatres varies depending on the geometry of the theatre, and on the fraction of area of the *cavea* occupied by the audience. For the theatres of Cassino and Benevento, the presence of the audience mildly varies the acoustic characteristics. For the theatre of Cassino, the absence of the stage building walls renders the acoustics poor. For the theatres of Taormina and Pompeii, with the presence of the audience there is a depletion of the energy in the first part of the impulse response, especially at low frequencies: in fact, the EDT values are very low. The theatres analysed present acoustics similar to those of other ancient theatres whose main features are clarity and the scarcity of the reverberating reflected field, and therefore live music of a symphony or classical orchestra or of a soloist is insufficiently supported by the acoustics of these theatres.

Koutsivitis *et al.* (2005) proposed a methodology (termed “AKROASIS”) that integrates high quality, real-time auralisation and visualization techniques. It was applied to the Epidaurus theatre, and the subjective performance of the interactive navigation in the theatre was found to be in very close agreement with the previous study of Vassilantonopoulos and Mourjopoulos (2003).

Moreover, in an architectural and acoustic study on 20 classical theatres in Greece, Barkas (2019) concludes that the addition of a removable stage during performances can provide useful reflections in addition to behaving like a sound barrier, which could improve the acoustic comfort in most of the theatres.

7. Conclusions

The Roman Empire extended across a vast geographic area. Roman theatres were a category of buildings designed for public assembly and performance and were influenced by a variety of geographical, climate, and cultural factors. It is evident that major morphologic differences between buildings of the same architectonic typology were produced due to the great distances between Roman provinces and towns, the lack of communication, and the variety in the performance practices. Many peculiar characteristics personalized each Roman theatre in agreement with their temporary layout. Furthermore, with the uninterrupted use of the theatres covering several centuries, successive architectonic interventions and alterations have been carried out in order to adapt the theatres to the requirements of society. The acoustics associated with these theatres present a crucial influence on the functional interpretation and state of conservation of these spaces. As a consequence of this architectural and acoustic diversity, further experimental campaigns are necessary in order to acoustically investigate these ancient spaces. Surface acoustic properties, such as absorption and scattering coefficients versus frequency, of the stone and local materials that make up the Roman theatres must be ascertained; in the pieces of research published on simulations, however, this information remains sparse. In the long list of Roman theatres indicated by the authors in Table 1, very few have been studied acoustically or have had their results published in international forums. The published pieces of work highlight the major role played by the diffraction of sound in the stands of the *cavea*, and the excellent acoustic conditions of the whole venue for the intelligibility of speech. For music, the low reverberation and clarity of the theatre can be mitigated in part by portable elements installed on the *scaena*.

In the case of unroofed spaces, the spatial characteristics of all the reflections during the decaying process differ greatly from those of an enclosed space. The prediction of reverberation in an unroofed space should not therefore be investigated solely via its decay rate and, in consequence, suitable alternative metrology should be proposed.

In simulations of open-air Roman theatres, the definition of the seating area exerts a major impact on the acoustics of the venue. A detailed seating area with rows and steps allows the horizontal reflections between seat rises and the *proscenium* to result in closer agreement with measured data. The scattering and diffraction from the sharp edges of the stone seats in an open-air theatre play a major role for the acoustics as opposed to roofed theatres where this is masked by roof reflections. In-situ acoustical measurements and evaluation of the materials of the theatre were necessary to obtain more information on surface properties. The results published highlight that the accuracy of the room acoustic simulations are dependent on the calculation methods of the software tools, and that an adjustment of the virtual model is needed for the complete set of temporal and energy acoustic parameters in their spatial and spectral distribution, if virtual reconstructions of the past and possible future refurbishments are required.

Even though these constructions are currently used as open-air theatres, in the face of the evidence, it is also useful for acousticians to set ancient Greco-Roman *odea* as examples of very early purposely-built buildings for music performances for large audiences, and as the progenitors of the later-era concert halls. The roofed versions of the *odeum* were similar to many modern-day concert halls of equivalent volume, although such halls would now have an approximate capacity of 1,000 listeners, as opposed to nearly 5,000 listeners for the *odea*.

Appendix

Table 1. List of Roman Theatres in the world.

COUNTRY in alphabetic order, Name	TOWN: coordinates	*Cavea* diameter [m]
ALBANIA (6)		
Theatre of Apollonia	Pojani: 40° 43′ 00″ N, 19° 28′ 00″ E	51.5
Theatre of Buthrotum	Butrint: 39° 44′ 44″ N, 20° 01′ 14″ E	24
SW Theatre of Byllis	Byllis: 40° 32′ 23″ N, 19° 44′ 17″ E	80.5
Theatre of Hadrianopolis	Sofratikë: 39° 59′ 47″ N, 20° 13′ 29″ E	58
Theatre of Oricum	Orikum: 40° 19′ 09″ N, 19° 25′ 47″ E	34
Theatre of Phoinike	Finiq: 39° 54′ 48″ N, 20° 03′ 23″ E	50–80*
ALGERIA (10)		
Theatre of Annaba	Annaba: 36° 52′ 52″ N, 07° 44′ 49″ E	55
Theatre of Calama	Guelma: 36° 28′ 02″ N, 07° 25′ 48″ E	58
Theatre of Cherchell	Cherchell: 36° 36′ 36″ N, 02° 11′ 48″ E	90
Theatre of Djemila	Djemila: 36° 19′ 14″ N, 05° 44′ 15″ E	62
Theatre of Khemissa	Khemissa: 36° 11′ 37″ N, 07° 39′ 21″ E	56.8

Table 1. [Cont.].

COUNTRY in alphabetic order, Name	TOWN: coordinates	*Cavea* diameter [m]
Theatre of Madaura	Madaura: 36° 4′ 29″ N, 07° 49′ 11″ E	53
Theatre of Rusicada	Skikda: 36° 52′ 00″ N, 06° 54′ 00″ E	82.4
Theatre of Skikda	Skikda: 36° 52′ 46″ N, 06° 54′ 18″ E	55
Theatre of Timgad	Timgad: 35° 29′ 03″ N, 06° 28′ 08″ E	63.6
Theatre of Tipasa	Tipasa: 36° 35′ 31″ N, 02° 26′ 58″ E	73
BULGARIA (1)		
Theatre of Plovdiv	Plovdiv: 42° 08′ 49″ N, 24° 45′ 04″ E	–
CROATIA (1)		
Theatre of Pula	Pula: 44° 52′ 12″ N, 13° 50′ 49″ E	–
CYPRUS (1)		
Theatre of Curium	Curium: 34° 39′ 51″ N, 32° 53′ 16″ E	52–62*
EGYPT (1)		
Theatre of Alexandria	Alexandria: 31° 11′ 40″ N, 29° 54′ 14″ E	33
FRANCE (25) *Gaul*		
Theatre of Aix-en-Provence	Aix-en-Provence: 43° 31′ 49″ N, 05° 26′ 14″ E	–
Theatre of Alba-la-Romaine	Alba-la-Romaine: 44° 33′ 35″ N, 04° 36′ 06″ E	73
Theatre of Arles	Arles: 43° 40′ 35″ N, 04° 37′ 47″ E	102
Theatre of Autun	Autun: 46° 57′ 09″ N, 04° 18′ 36″ E	148
Theatre of Bouchauds	Bouchauds: 46° 46′ 53″ N, 00° 00′ 22″ W	105.6
Theatre of Drevant	Drevant: 46° 41′ 35″ N, 02° 31′ 21″ E	85
Theatre of Eu	Eu: 50° 01′ 18″ N, 01° 27′ 55″ E	–
Theatre of Fréjus	Fréjus: 43° 26′ 13″ N, 06° 44′ 17″ E	83.81
Theatre of Gisacum	Gisacum: 49° 00′ 12″ N, 01° 14′ 10″ E	102.5
Theatre of Jublains	Jublains: 48° 15′ 17″ N, 00° 29′ 39″ E	79
Theatre of Lillebonne	Lillebonne: 49° 31′ 03″ N, 00° 32′ 13″ E	109
Theatre of Lyon	Lyon: 45° 45′ 35″ N, 04° 49′ 11″ E	108.5
Theatre of Lyon (odeum)	Lyon: 45° 45′ 31″ N, 04° 49′ 11″ E	73
Theatre of Mandeure	Mandeure: 46° 26′ 57″ N, 06° 47′ 46″ E	142
Theatre of Mauves-sur-Loire	Mauves-sur-Loire: 47° 17′ 46″ N, 01° 23′ 36″ W	54
Theatre of Naintré	Naintré: 466° 45′ 42″ N, 00° 30′ 44″ E	114
Theatre of Orange (Beckers, Borgia, 2009)	Orange: 44° 08′ 09″ N, 04° 48′ 32″ E	103.63
Theatre of Saint-Marcel	Saint-Marcel: 46° 35′ 57″ N, 01° 30′ 35″ E	61–85.5*
Theatre of Saoft-Germain-d′Esteuil	Saint-Germain-d′Esteuil: 45° 16′ 45″ N, 00° 50′ 28″ E	58
Theatre of Soissons	Soissons: 49° 22′ 54″ N, 03° 19′ 24″ E	144
Theatre of Toulouse	Toulouse: 43° 36′ 15″ N, 01° 26′ 37″ E	84
Theatre of Vaison-la-Romaine	Vaison-la-Romaine: 44° 14′ 38″ N, 05° 04′ 32″ E	96
Theatre of Vendeuil-Caply	Vendeuil-Caply: 49° 36′ 29″ N, 02° 18′ 02″ E	81
Theatre of Vienne	Vienne: 45° 31′ 29″ N, 04° 52′ 43″ E	90
Theatre of Vieux-Poitiers	Vieux: 46° 45′ 42″ N, 00° 30′ 43″ E	112
GERMANY (1) *Germania*		
Theatre of Maguncia	Mainz, Rheinland-Pfalz: 49° 59′ 35″ N, 08° 16′ 41″ E	116.25
GREECE (11)		
Odeum of Agrippa	Athens: 37° 58′ 30.36″ N, 23° 43′ 23.52″ E	–
Odeum of Ancient Agora of Thessaloniki	Thessaloniki: 40° 38′ 15″ N, 22° 56′ 47″ E	–
Odeum of Ancient Corinth	Corinth: 37° 54′ 21″ N, 22° 52′ 38″ E	–
Odeum of Gortyna (Crete)	Gortyna: 35° 03′ 47″ N, 24° 56′ 49″ E	–

Table 1. [Cont.].

COUNTRY in alphabetic order, Name	TOWN: coordinates	*Cavea* diameter [m]
Odeum of Herodes Atticus (Vassilantonopoulos, Mourjopoulos, 2009)	Athens: 37°58′ 14.72″ N, 23°43′ 28″ E	–
Odeum of Kos	Kos: 36° 53′ 23″ N, 27° 17′ 05″ E	–
Odeum of Nikopolis	Preveza: 39° 00′ 40″ N, 20° 43′ 45″ E	–
Odeum of Patras (Vassilantonopoulos *et al.*, 2005; Vassilantonopoulos, Mourjopoulos, 2003)	Patras: 38° 14′ 36″ N, 21° 44′ 18″ E	–
Theatre of Dion	Dion-Olimpos: 40° 10′ 35″ N, 22° 29′ 32″ E	16.45
Theatre of Gortyna (Crete)	Gortyna: 35° 03′ 48″ N, 24° 56′ 45″ E	–
Theatre of Nikopolis	Preveza: 39° 01′ 25″ N, 20° 44′ 15″ E	–
HUNGARY (1)		
Theatre of Tác	Tác: 47° 05′ 27″ N, 18° 25′ 19″ E	–
ITALY (57)		
Theatre of Amiternum	San Vittorino: 42° 24′ 14″ N, 13° 18′ 35″ E	80
Theatre of Anzio	Anzio: 41° 27′ 18″ N, 12° 37′ 43″ E	44
Theatre of Aosta (Gugliermetti *et al.*, 2008; Rindel, 2013)	Aosta: 45° 44′ 19″ N, 07° 19′ 20″ E	62.7
Theatre of Asculum	Ascoli Piceno: 41° 51′ 13″ N, 13° 34′ 07″ E	99.5
Theatre of Benevento (Alfano *et al.*, 2015; Iannace,Trematerra, 2014)	Benevento: 41° 07′ 50″ N, 14° 46′ 18″ E	93
Theatre of Brescia	Brescia: 45° 32′ 24″ N, 10° 13′ 36″ E	90
Theatre of Calvi Risorta	Calvi Risorta: 41° 12′ 00″ N, 14° 07′ 56″ E	75.4
Theatre of Cassino (Iannace,Trematerra, 2014)	Cassino: 41° 29′ 00″ N, 13° 49′ 16″ E	53.5
Theatre of Catania	Catania: 37° 30′ 10″ N, 15° 05′ 02″ E	87–102*
Theatre of Chieti	Chieti: 42° 20′ 50″ N, 14° 09′ 48″ E	84
Theatre of Cividate Camuno	Cividate Camuno: 45° 56′ 39″ N, 10° 16′ 10″ E	56
Theatre of Civita Ansidonia	Civita Ansidonia: 42° 16′ 58″ N, 13° 37′ 26″ E	58
Theatre of Falerone	Falerone: 43° 06′ 08″ N, 13° 30′ 00″ E	49.2
Theatre of Ferento	Ferento: 42° 29′ 18″ N, 12° 07′ 56″ E	54
Theatre of Fermo	Fermo: 43° 09′ 41″ N, 13° 42′ 56″ E	75
Theatre of Fiesole (Shankland,1968)	Fiesole: 43° 48′ 28″ N, 11° 17′ 37″ E	67
Theatre of Florence	Florence: 43° 46′ 08″ N, 11° 15′ 19″ E	100
Theatre of Gioiosa Ionica	Gioiosa Ionica: 38° 18′ 05″ N, 16° 19′ 58″ E	47.4
Theatre of Grumento Nova	Grumento Nova: 40° 17′ 00″ N, 15° 54′ 19″ E	48
Theatre of Gubbio	Gubbio: 43° 21′ 07″ N, 12° 34′ 21″ E	70.4
Theatre of Lecce	Lecce: 40° 21′ 05″ N, 18° 10′ 13″ E	75.2
Theatre of Liternum	Liternum: 40° 55′ 17″ N, 14° 01′ 48″ E	–
Theatre of Locri	Locri: 38° 12′ 58″ N, 16° 13′ 43″ E	65
Theatre of Luni	Luni: 44° 03′ 54″ N, 10° 01′ 13″ E	45
Theatre of Milan	Milan: 45° 27′ 27″ N, 09° 10′ 43″ E	95
Theatre of Minturno	Minturno: 41° 14′ 33″ N, 13° 46′ 06″ E	78.3
Theatre of Montegrotto	Montegrotto: 45° 19′ 47″ N, 11° 47′ 33″ E	28
Theatre of Napoli	Napoli: 40° 51′ 08″ N, 14° 15′ 24″ E	102
Theatre of Nora	Nora: 38° 59′ 04″ N, 09° 00′ 59″ E	39
Theatre of Ostia (Gugliermetti *et al.*, 2008)	Ostia: 41° 45′ 21″ N, 12° 17′ 30″ E	65

Table 1. [Cont.].

COUNTRY in alphabetic order, Name	TOWN: coordinates	*Cavea* diameter [m]
Theatre of Ostra Vetere	Ostra Vetere: 43° 35′ 05″ N, 13° 05′ 09″ E	44.6
Theatre of Otricoli	Otricoli: 42° 24′ 54″ N, 12° 27′ 55″ E	79
Theatre of Pietrabbondante	Pietrabbondante: 41° 44′ 23″ N, 14° 23′ 15″ E	54
Theatre of Pompei (large theatre) (Alfano *et al.*, 2015; Iannace *et al.*, 2013)	Pompei: 40° 44′ 56″ N, 14° 29′ 18″ E	60
Theatre of Pompei (odeum) (Berardi *et al.*, 2016)	Pompei: 40° 44′ 56″ N, 14° 29′ 20″ E	28.6 × 34.8**
Theatre of Posillipo (large theatre) (Iannace, Berardi, 2017)	Posillipo : 40° 47′ 41″ N, 14° 11′ 05″ E	47
Theatre of Posillipo (odeum)	Posillipo : 40° 47′ 38″ N, 14° 11′ 05″ E	26
Theatre of San Gemofi	San Gemini: 42° 38′ 22″ N, 12° 33′ 36″ E	62.7
Theatre of Sepino	Sepino: 41° 26′ 04″ N, 14° 37′ 02″ E	61.5
Theatre of Sessa Aurunca	Sessa Aurunca: 41° 14′ 04″ N, 13° 55′ 50″ E	80
Theatre of Spoleto	Spoleto: 42° 43′ 59″ N, 12° 44′ 06″ E	72.2
Theatre of Suasa	Suasa: 47° 37′ 30″ N, 12° 59′ 10″ E	–
Theatre of Taormina (Sato *et al.*, 2002)	Taormina: 37° 51′ 08″ N, 15° 17′ 32″ E	109
Theatre of Teano	Teano: 41° 14′ 54″ N, 14° 04′ 21″ E	85
Theatre of Teramo	Teramo: 42° 39′ 29″ N, 13° 42′ 15″ E	78
Theatre of Trieste	Trieste: 45° 38′ 57″ N, 13° 46′ 18″ E	64.4
Theatre of Turin	Turin: 45° 04′ 26″ N, 07° 41′ 08″ E	76
Theatre of Tuscolo	Tuscolo: 41° 47′ 54″ N, 12° 42′ 38″ E	45
Theatre of Urbino	Urbino: 43° 43′ 20″ N, 12° 38′ 14″ E	65
Theatre of Urbisaglia	Urbisaglia: 43° 11′ 56″ N, 13° 22′ 51″ E	90
Theatre of Venafro	Venafro: 41° 29′ 08″ N, 14° 02′ 24″ E	95
Theatre of Vene Bagienna	Vene Bagienna: 44° 33′ 33″ N, 07° 51′ 18″ E	57.5
Theatre of Ventimiglia	Ventimiglia: 43° 47′ 21″ N, 07° 37′ 32″ E	52
Theatre of Verona	Verona: 45° 26′ 51″ N, 11° 00′ 07″ E	105
Theatre of Vicenza	Vicenza: 45° 32′ 37″ N, 11° 32′ 48″ E	81.9
Theatre of Villa Potensa	Villa Potensa: 43° 19′ 40″ N, 13° 25′ 26″ E	71.92
Theatre of Volterra	Volterra: 43° 24′ 12″ N, 10° 51′ 36″ E	63
ISRAEL (4)		
Theatre of Beth-Shean	Beth-Shean: 32° 29′ 46″ N, 35° 29′ 56″ E	87
Theatre of Caesarea Maritima	Caesarea Maritima: 32° 29′ 46″ N, 34° 53′ 27″ E	100
Theatre of Saffuriyye	Saffuriyye: 32° 44′ 44″ N, 35° 16′ 43″ E	74
Theatre of Tiberias	Tiberias: 32° 47′ 23″ N, 35° 31′ 29″ E	–
JORDAN (6)		
Theatre of Aman (large theatre)	Aman: 31° 57′ 06″ N, 35° 56′ 21″ E	102
Theatre of Aman (odeum)	Aman: 31° 57′ 08″ N, 35° 56′ 24″ E	38
Theatre of Gabara	Gabara: 32° 39′ 20″ N, 35° 40′ 40″ E	80
Theatre of Jerash (north theatre) (Odeum)	Jerash: 32° 16′ 57″ N, 35° 53′ 33″ E	59.3
Theatre of Jerash (south theatre) (Beckers, Borgia, 2009; Farina, Tronchin, 2013)	Jerash: 32° 16′ 36″ N, 35° 53′ 21″ E	76
Theatre of Petra	Petra: 30° 19′ 29″ N, 35° 26′ 50″ E	95
LEBANON (1)		
Theatre of Byblos	Byblos: 34° 07′ 09″ N, 35° 38′ 42″ E	–

Table 1. [Cont.].

COUNTRY in alphabetic order, Name	TOWN: coordinates	*Cavea* diameter [m]
LUXEMBOURG (1)		
Theatre of Dalheim	Dalheim: 49° 32′ 35.16″ N, 06° 15′ 29.9″ E	62.4
LYBIA (5)		
Theatre of Leptis Magna	Lebda: 32° 38′ 18″ N, 14° 17′ 26″ E	87.6
Theatre of Sabratha	Sabratha: 32° 48′ 19″ N, 12° 29′ 7″ E	92.6
Theatre of Shahat (Theatre 1)	Shahat: 32° 49′ 04″ N, 21° 51′ 29″ E	65
Theatre of Shahat (Theatre 2)	Shahat: 32° 49′ 06″ N, 21° 51′ 28″ E	52
Theatre of Shahat (Theatre 3)	Shahat: 32° 49′ 12″ N, 21° 51′ 26″ E	50
MACEDONIA (3)		
Theatre of Bitolj	Bitolj: 41° 00′ 41″ N, 21° 20′ 32″ E	58.5
Theatre of Skopje	Skopje: 42° 01′ 02″ N, 21° 23′ 37″ E	98
Theatre of Pustogradske	Pustogradske: 41° 33′ 06″ N, 21° 58′ 29″ E	90
PORTUGAL (3) *Lusitania*		
Theatre of Braga	Braga: 41° 33′ 1.2″ N, 08° 25′ 12.2″ W	–
Theatre of Evora	Evora: 38° 34′ 00″ N, 07° 54′ 00″ W	–
Theatre of Lisbon	Lisbon: 38° 42′ 37″ N, 09° 07′ 57″ W	80
SPAIN (22) *Hispania*		
Theatre of Acinipo	Ronda: 36° 49′ 54″ N, 05° 14′ 25″ W	62
Theatre of Baelo Claudia	Bolonia: 36° 05′ 27″ N, 05° 46′ 32″ W	70
Theatre of Baetulo	Badalona: 41° 27′ 07″ N, 02° 14′ 45″ E	–
Theatre of Bilbilis	Calatayud: 41° 22′ 54″ N, 01° 36′ 14″ W	78.2
Theatre of Cadiz (Álvarez-Corbacho *et al.*, 2018)	Cádiz: 36° 31′ 42″ N, 06° 17′ 38″ W	118
Theatre of Cartagena	Cartagena: 37° 35′ 58″ N, 01° 36′ 14″ W	87.2
Theatre of Carteia	San Roque: 36° 12′ 35″ N, 05° 24′ 05″ W	–
Theatre of Clunia	Peñalba de Castro: 41° 47′ 03″ N, 00° 59′ 03″ W	96
Theatre of Cordoba	Córdoba: 37° 52′ 55″ N, 04° 46′ 41″ W	120
Theatre of Guadix	Guadix: 37° 18′ 08″ N, 03° 08′ 14″ W	73
Theatre of Italica (Álvarez-Corbacho *et al.*, 2014)	Santiponce: 37° 26′ 24″ N, 06° 02′ 19″ W	75.76
Theatre of Malaga	Málaga: 36° 43′ 16″ N, 04° 25′ 01″ W	64.5
Theatre of Medellin	Medellín: 38° 57′ 58″ N, 05° 57′ 21″ W	63
Theatre of Merida	Mérida: 38° 54′ 55″ N, 06° 20′ 19″ W	86.63
Theatre of Osuna	Osuna: 37° 14′ 20″ N, 05° 05′ 44″ W	32.5
Theatre of Pollentia	Alcudia de Pollensa: 39° 51′ 03″ N, 03° 07′ 13″ E	31
Theatre of Regina Turdulorum (Álvarez-Corbacho *et al.*, 2015)	Casas de Reina: 38° 12′ 12″ N, 05° 57′ 13″ W	64
Theatre of Sagunto	Sagunto: 39° 40′ 36″ N, 00° 16′ 41″ W	85
Theatre of Segobriga (Álvarez-Corbacho *et al.*, 2019)	Saelices: 39° 53′ 10″ N, 02° 48′ 45″ W	65
Theatre of Singilia Barba	Antequera: 37° 01′ 57″ N, 04° 37′ 51″ W	52
Theatre of Tarragona	Tarragona: 41° 06′ 46″ N, 01° 14′ 58″ W	70.8
Theatre of Zaragoza	Zaragoza: 41° 39′ 07″ N, 00° 52′ 39″ W	105
SWITZERLAND (3)		
Theatre of Augst	Augst: 47° 31′ 59″ N, 07° 43′ 18″ E	99.45
Theatre of Avenches	Avenches: 46° 52′ 49″ N, 07° 02′ 56″ E	106
Theatre of Lenzburg	Aarau: 47° 23′ 42″ N, 08° 11′ 27″ E	74

Table 1. [Cont.].

COUNTRY in alphabetic order, Name	TOWN: coordinates	*Cavea* diameter [m]
SYRIA (8)		
Theatre of Apamea	Mudanya: 35° 25′ 00″ N, 36° 23′ 41″ E	–
Theatre of Baniyas	Baniyas: 33° 14′ 44″ N, 35° 41′ 34″ E	–
Theatre of Bosra	Bosra: 32° 31′ 02″ N, 36° 28′ 52″ E	88.3
Theatre of Cirro	Nebi Uri: 36° 44′ 39″ N, 36° 57′ 32″ E	115
Theatre of Dura Europos	Salhiye: 34° 44′ 59″ N, 40° 43′ 42″ E	13.6 ×12.5**
Theatre of Gabala	Djeblé: 35° 21′ 42″ N, 35° 55′ 28″ E	90
Theatre of Palmyra (Álvarez-Corbacho *et al.*, 2017)	Palmyra: 34° 33′ 02″ N, 38° 16′ 06″ E	47.72
Theatre of Shahba	Shahba: 32° 51′ 11″ N, 36° 37′ 36″ E	–
TUNISIA (9)		
Theatre of Bulla Regia	Hammam Daradji: 36° 33′ 32″ N, 08° 45′ 25″ E	60
Theatre of Carthage	Carthage: 36° 51′ 28″ N, 10° 19′ 46″ E	104
Theatre of Chemtou	Chemtou: 36° 29′ 29″ N, 08° 34′ 18″ E	64
Theatre of Cillium	Kasserine: 35° 10′ 03″ N, 08° 47′ 58″ E	53
Theatre of Dougga	Dougga: 36° 25′ 25″ N, 10° 19′ 46″ E	63.5
Theatre of Haïdra	Haïdra: 35° 33′ 59″ N, 08° 27′ 27″ E	65
Theatre of Medeina	Medeina: 35° 52′ 22″ N, 08° 47′ 11″ E	57.5
Theatre of Sbeitla	Sbeitla: 35° 14′ 23″ N, 09° 07′ 21″ E	59
Theatre of Utique	Utique: 37° 03′ 25″ N, 10° 03′ 43″ E	110
TURKEY (14)		
Theatre of Aphrodisias (Rindel *et al.*, 2006)	Geyre: 37° 42′ 25″ N, 28° 43′ 31″ E	90
Theatre of Aphrodisias (Odeum) (De Heras-Ciechomski *et al.*, 2004; Farina, Tronchin, 2013)	Geyre: 37° 42′ 33″ N, 28° 43′ 25″ E	45.6
Theatre of Aspendus (Gade *et al.*, 2005; Rindel, 2013)	Belkiz: 36° 56′ 21″ N, 31° 10′ 21″ E	95.48
Theatre of Bodrum	Bodrum: 37° 02′ 23″ N, 27° 25′ 17″ E	86
Theatre of Efesus (Odeum)	Selçuk: 37° 56′ 12″ N, 27° 20′ 41″ E	47.5
Theatre of Efesus (Beckers, Borgia, 2009)	Selçuk: 37° 56′ 27″ N, 27° 20′ 32″ E	142
Theatre of Hierapolis	Pamukkale: 37° 55′ 36″ N, 29° 07′ 33″ E	103
Theatre of Miletus	Balat: 37° 31′ 49″ N, 27° 16′ 31″ E	139.8
Theatre of Myra	Dernek: 36° 15′ 32″ N, 29° 59′ 07″ E	68
Theatre of Nysa	Sultanhisar: 37° 54′ 12″ N, 28° 08′ 44″ E	115
Theatre of Perge	Aksu: 36° 57′ 31″ N, 30° 51′ 05″ E	112.5
Theatre of Selge	Zerk: 37° 13′ 46″ N, 31° 07′ 38″ E	104
Theatre of Side	Side: 36° 46′ 05″ N, 31° 23′ 26″ E	–
Theatre of Troia (Odeum)	Hisarlik: 36° 57′ 26″ N, 26° 14′ 20″ E	44.5
UNITED KINGDOM (4) *Britannia*		
Theatre of Canterbury	Canterbury: 51° 16′ 44″ N, 01° 04′ 47″ E	82
Theatre of Cirencester	Cirencester: 51° 43′ 09″ N, 01° 58′ 17″ W	58
Theatre of Colchester	Colchester: 51° 53′ 19″ N, 00° 54′ 13″ E	–
Theatre of Saint Albans	Saint Albans: 51° 45′ 13.75″ N, 00° 21′ 30.8″ W	57.5

* Estimated between the two values, ** rectangular *cavea*.

Acknowledgements

This work is funded by the ERDF and the Spanish Ministry of Economics, Industry, and Competitiveness with reference BIA2017-85301-P.

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