JASA REVIEW-ARTICLE

Acoustical aspects of the development of Greek theaters in the 4th century B.C.E.

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ABSTRACT:
In ancient Greece, the 4th century B.C.E. was a time of rapid development in arts, culture, science, politics, and theater architecture. The first part of this article describes the origin and use of the Greek theater building and its connection to the Dionysus cult and festivals with musical and drama competitions. Next, scientific context is discussed as a background regarding the highly skilled architects who designed these theaters. The 4th century B.C.E. is characterized by the blooming of the sciences, especially mathematics, strongly stimulated by Plato's Academy near Athens. The architecture of the theater changed within this century. While earlier theaters had mostly rectilinear seat-rows, symmetry and a stricter geometry started to characterize theater design. In this study, six theaters were selected for acoustical analysis: three of them with rectilinear shapes, and three of the well-known semicircular form. Acoustical analyses show that the archaeologically demonstrated shift in theater design from a simple rectilinear shape to the historically canonical semicircular shape was a way to increase theater capacity and at the same time improve the acoustics. Acoustical analyses reveal some of the design principles that can explain the excellent acoustics of these theaters and the applied knowledge of their designers.
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I. INTRODUCTION

Theaters[1] are among the most spectacular architectural creations of ancient Greece, and the best preserved of them are even today admired for their excellent acoustics. This gives rise to many questions: Why did the Greeks build so many theaters? Why are they so big? What were they used for? How much did their architects know about acoustics? Are there some (now forgotten) secrets that explain the excellent acoustics, for instance, an acoustical basis to the rumors about theaters with sounding vessels? This article applies architectural acoustical modeling together with classical studies to answer these questions.

Ancient Greek theaters were open-air performance spaces related to religion (Dionysus cult) and designed for dramatic performance that required good speech intelligibility. The theaters were connected to the very beginning of drama by the writers Aeschylus, Sophocles, and Euripides in the 5th century B.C.E. (Bieber, 1961, pp. 1–17). Although there are no two identical theaters in the archaeological record, most Greek theaters have been designed in a very similar way, with a central circular *orchestra*, a semicircular audience area (*koilon*) with ascending rows of seats, and a scene-building (*skene*) on the opposite side. However, at the start of the 4th century B.C.E., the theaters looked different, mostly with rectilinear rows of seats, the *orchestra* could have an irregular shape, and the scene-building was usually of a wooden construction, if there was any at all.[2]

The two basic theatrical performances, tragedy and comedy, were developed in Athens during the 6th and 5th centuries B.C.E., and the popularity of the theaters grew rapidly during the 4th century B.C.E., which is known as the late Classical period (400–323 BCE). The popularity of theater may also be related to the political situation of democracy with freedom of speech (Beard, 2013, pp. 218–223; Johansen, 1985). The idea of democracy developed in Athens in the 5th century B.C.E. and other Greek city-states followed the Athenian model. Thus, the dramatic performances often hinted made jokes referring to persons of high rank.

The semicircular shape of the seat-rows was introduced in the middle of the 4th century B.C.E., but we do not know where or when it was used for the first time. The theaters in the 5th and early 4th century B.C.E. had rectilinear seat-rows and known examples are in Argos, Syracusa, Thorikos, and the Lenaion theater in Athens (Bieber, 1961, p. 51; Mitens, 1988, p. 20; Sear, 2006, p. 191; Frederiksen, 2015, pp. 81–84). One of the most important theaters in the 4th century B.C.E. was the theater of Dionysus Eleuthereus in Athens and around 320 B.C.E. This theater was enlarged and reconstructed following the principle with a circular *orchestra* and semicircular seat-rows (Papastamati-von Moock, 2014, pp. 72–74; Sear, 2006, pp. 388–389).

Also, in Makedonia, there was a great tradition for theater, and this may be the reason that Alexander the Great (356–323 B.C.E.) was seriously interested in theaters with their associated competitions and festivals. Already in 348 B.C.E. after the destruction of Olynthus, Alexander's father

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Philip organized dramatic competitions, and Alexander did the same after the sack of Thebes in 335 B.C.E. Thus, Alexander separated theater from its religious roots and used it politically to demonstrate his military success and to consolidate his popularity among the soldiers (Le Guen, 2014). During Alexander's military expedition to the East, he was followed by writers, actors, and musicians. He celebrated many of his greater victories by arranging theatrical events and/or athletic contests and equestrian games; as many as 20 events were recorded between 333 and 323 B.C.E. (Le Guen, 2014, pp. 251–255). Of course, during this military campaign, there were no permanent theaters available, so we can imagine that he instructed his soldiers to build temporary theaters. Some of Alexander's celebrations in India were arranged on river banks (Le Guen, 2014, p. 253).

An overview of ancient Greek and Roman theaters and their acoustics was recently presented by Girón *et al.* (2020). Through computer simulations of reconstructed models of some typical examples of theaters, we can illustrate the acoustical qualities and weaknesses of various Greek theater designs as they developed during the 4th century B.C.E. A similar approach was applied by Chourmouziadou and Kang (2008). However, while their study considered examples in a wide span of several hundred years—from the Minoic theater via Greek to Roman theaters—the present work focuses on the development of theater architecture in Greece within a narrow period of around one hundred years.

II. ORIGINS OF GREEK THEATER

A. Festivals

The origin of Greek theater relates closely to the festival tradition that emerged in the 6th and 5th century B.C.E. The most famous are the Olympic Games in Olympia, the Epidauria in Epidaurus, and the Panathenaic Games in Athens. These competitive celebrations occurred every four years while other festivals were held on an annual basis, in the same month every year. Annual festivals included the Rural Dionysia in December–January, the City Dionysia in the Spring, and the Lenaia in Athens with dramatic competitions (Bieber, 1961, pp. 51–53). The core of these festivals were competitions in a variety of disciplines, not only athletics, but also oratorical, musical, and dramatic events. The acoustical and spatial needs for these events were different, and ideally, three different kinds of spaces were needed if all disciplines should be covered in the festival: a stadium, an *odeion*, and a theater.

A stadium is a sports field with seat-rows for spectators on the sides. Stadia were built for athletic competitions, e.g., foot races, and one of the earliest is the one in Epidaurus from the 5th century B.C.E. (Fig. 1). Note the rectilinear seat-rows on both sides. The length of the stadium was set to 600 feet = 1 stade (approximately 180 m).[3] There were no acoustical requirements for the stadia.

FIG. 1. The ancient stadium at Epidaurus. Photo by author 2011.

The musical disciplines for the competitions included instrumental and vocal performances. Other competitions involved singing or the recitation of poems accompanied by a stringed instrument with a relatively weak sound, either the *lyre* or the bigger *cithara* (Buchner, 1958, p. 17). Therefore, such performances would preferably take place inside a roofed building, the *odeion* (meaning a place for singing). The Greek *odeia* were mostly wooden buildings, and due to the challenges of preservation, very few traces were found from the early period. The *odeion* of Pericles in Athens from the 5th century B.C.E. was a nearly square building next to the Dionysus theater at the Southern slopes of Acropolis (Bieber, 1961, p. 59), see Fig. 2. It had stone columns carrying the roof, which probably had the shape of a flat pyramid or a large parasol. At the time the *odeion* was built (446–442 B.C.E.), the theater had still temporary rectilinear wooden seating and no scene building.

The theater was the third kind of space for the festivals. It has religious roots connecting it to temples, and its origin might simply be the stairs in front of a temple as used for

FIG. 2. A proposed three-dimensional (3D) reconstruction of the Dionysos theater and Pericles' *odeion* at the south slope of Acropolis around 400 B.C.E. Courtesy of Dimitrios Tsalkanis, www.AncientAthens3d.com.

spectators of the ritual offerings and performances taking place in front of the temple. As early as the 6th century B.C.E., there were three different kinds of performances in the theater: tragedy, comedy, and satyr plays. While the tragedy typically displayed gods and heroes, it is no secret that the comedy and satyr plays were more profane or directly obscene (Thomsen, 1985). Aristotle suggested that comedy originated from "those who lead off the phallic processions" that were a part of the Dionysia (Csapo, 1997, p. 265). This explains the obscene nature of the first form of comedy, Old Comedy, in which actors sometimes wore a red leather phallus.

B. Dionysia

The Dionysia were annual celebrations held after the harvest (around December) and again in the early spring. The Dionysia included a phallic procession that ended in front of a temple or in a theater where an offering took place, followed by scenic performances and various competitions that could last for several days. In addition to tragedies and comedies, the Dionysian contests included dance and singing in honor of *Dionysus*, the god of wine and fertility. Ancient hymns, *dithyrambs*, were performed by a *chorus* (up to 50 men or boys) singing and dancing in circular formation accompanied by musicians playing the *aulos*. The members of the chorus may have been dressed as *satyrs* (half-goats, half-men). The mosaic shown in Fig. 3 shows the preparations for a satyr play.

C. Music and plays

Another mosaic in Fig. 4 shows musicians performing in a theater, playing the *aulos*, a pair of *cymbals*, and the *tympanon* (a flat drum), all being loud musical instruments

FIG. 3. A group of actors preparing for a satyr play. The musician is practicing the *aulos* and an actor has assistance to get into a costume. Mosaic from Pompeii, now at the National Archaeological Museum of Naples. Photo: (C) 2006 Sergey Sosnovskiy (https://ancientrome.ru/art/artworken/img.htm?id=2128); licensed under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license (https://creativecommons.org/licenses/by-sa/4.0/).

FIG. 4. Scene from a theater with two actors playing a pair of *cymbals* and the *tympanon* accompanied by a female *aulos* player. Mosaic from Pompeii, now at the National Archaeological Museum of Naples. Photo: (C) 2006. Sergey Sosnovskiy (https://ancientrome.ru/art/artworken/img.htm?id=2003); licensed under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license (https://creativecommons.org/licenses/by-sa/4.0/).

that could be used effectively in an outdoor environment. The small figure to the left is an assisting slave (slaves were often depicted in half-size). It has been suggested that the motive is a scene from the comedy "The possessed girl" by the dramatist, Menander (c. 342–291 B.C.E.) (Dunbabin, 1999, p. 47). The "signature" of the artist is seen on top: Dioskourides of Samos, a master of mosaics from the 3rd to 2nd century B.C.E.

It is an interesting and somewhat surprising fact that several mosaics from Pompeii have Greek origins and motives that date back to the 4th century B.C.E. Before Pompeii became a Roman province in 80 B.C.E., the city was inhabited by the Samnites, and the large Greek theater of Pompeii dates to the 3rd century B.C.E. The Samnites controlled much of Southern Italy before the 4th century B.C.E., and Pompeii had connections to Greek culture. There was a continuity between the earlier Samnite phase and the Roman period after the conquest in 80 B.C.E. Wealthy Romans who settled in Pompeii also admired ancient Greek art and culture and decorated their home with paintings, mosaics, and sculptures that were copies of older Greek masterpieces, which is obvious from the excavations of Pompeii (Beard, 2008, pp. 120–151).

D. The aulos

One of the most important musical instruments was the *aulos* (Baines, 1967, pp. 194–208). It is not a flute (as it is often called in the literature) but belongs to the same group of instruments as the modern oboe. The instrument was played in a pair of two (*auloi*) allowing two tones to be played simultaneously. The sound of the instrument was penetrating and exciting like that of the bagpipe. Being a

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FIG. 5. Marble relief with a scene from a comedy. The National Archaeological Museum of Naples. Photo: (C) 2015. Ilya Shurygin, https://ancientrome.ru/art/artworken/img.htm?id=7397.

FIG. 6. Apollo and Marsyas in musical contest with *cithara* and *aulos*. Marble relief found at Mantinea, Arkadia, c. 330–320 BCE. National Museum, Athens. Photo: Courtesy of Søren Koustrup.

loud instrument, competitions for *aulos* players were held in the theater. The *aulos* was used in processions, accompanying the dance, and in comedies. The relief shown in Fig. 5 has been interpreted to show a scene from a comedy. Here, the *aulos* is played together with performing actors.

The *aulos* was a loud instrument and the air pressure in the mouth could be very high; thus, the *aulos* player is often shown wearing a pair of strings around the neck for support of the cheeks, as can be seen in Fig. 3. The instrument was difficult to master, and *aulos* players were professional musicians, who could win high prizes in the contests at the festivals. Female *aulos* players were common, but in the contests for best *aulos* player, only male musicians could participate (Bélis, 1999, p. 37). *Aulos* players featured on many occasions, e.g., in funerals and the army (Bélis, 1999, p. 77). It is thought that good *aulos* players mastered the technique of "circular breathing," which means that the music could be played continuously without interruption, very much like the bagpipe. Circular breathing is used today for playing the Australian *didgeridoo*.

The *aulos* is a very old musical instrument that can be traced to ancient Egypt. Today, the only known descendent of the *aulos* is the *launeddas* an instrument still used on the island of Sardinia (Bentzon, 1969). It consists of a set of three single-reed pipes, one drone, and two chanters. All three pipes are mouth-blown simultaneously using circular breathing.

E. The cithara

The *cithara* is a plucked string instrument with seven strings. It can be considered a professional version of the *lyre*, which is a smaller and lighter instrument with less sound power. The strings of the *cithara* are fixed to a sounding wooden box below and on top they are knotted around a crossbar. The strings pass over a flat sound bridge connected to the sounding box. Usually, there are seven strings, and they are played with a plectrum in the right hand, while the left hand can damp the strings. Due to the large sound box and the high tension of the strings, the sound of the cithara could be quite loud.

As for the aulos, festivals also included contests for *cithara* players, and for singing with the *cithara*. Figure 6 shows the myth of a musical contest between Apollo with the *cithara* and the satyr Marsyas with the *aulos*. The person in the middle holds a knife. According to the myth, Apollo won the competition and ordered the unfortunate Marsyas to be flayed as a punishment for challenging the god.

F. The function of the orchestra

The central part of the ancient Greek theater was the *orchestra*, which was the place for dance and singing by the *chorus*. The word *orchestra* comes from the Greek *orcheomai*, to dance. However, the *orchestra* had also an acoustical function. There is no doubt that the ancient designers of the theaters were aware of the importance of acoustical reflections in the theater, and in particular, the use of the *orchestra* surface as a sound reflector. The surface of the *orchestra* was the subject of a question raised by Aristotle (1926): "Why are choruses less distinct when the *orchestra* is covered with straw? Is it due to the roughness that the voice falling on a surface that is not smooth is less united so that it is less? For it is not continuous. Just in the same way light shines more on a smooth surface because it is not interrupted by any obstruction."[4]

Marcus Vitruvius Pollo (c. 80–15 B.C.E.), in his Ten Books on Architecture (Vitruvius Pollio, 2001), draws extensively on older Greek writings on architecture and building technology, none of which exists today. Although he lived some 300 years later than the case-study theaters examined here, his writing on the design of theaters is largely a translation of ancient Greek treatises. Four different kinds of sonic reflections in a theater are explained; the Greek terms for the reflections are quoted, and in translation, they are named *dissonant*, *circumsonant*, *resonant*, and *consonant* (Vitruvius, 5, 8, 1). Some are destructive like the *resonant* reflection, which can produce an echo. Most beneficial are the *consonant* reflections, "in which the voice, reinforced from below, rises with this increment and reaches the ears with precise clarity" (Vitruvius, 5, 8, 2).[5] From this description, it is concluded that the consonant reflections are those from the *orchestra*. The surface of the *orchestra* is nearly always beaten earth, which is dense and hard. The exceptions are *orchestra*s paved with even harder stone or marble, which became common after the 4th century BCE (Sear, 2006, pp. 80–82).

G. The function of the pinnacles

Attesting to architectural knowledge of theater acoustics in this period is the historical account regarding the *pinnacles* (the decorated facade of the *proskenion*), normally made of painted wooden boards. Alexander the Great asked his architect if he could make the *proskenion* in bronze for his new theater at Pella. The architect would not permit this material change because it would alter the actors' voices (*Moralia*, Plutarch, 1096b). This story implies that the architect was both concerned about the acoustics of the theater and had knowledge of material properties that influence architectural acoustics and their role in supporting vocal performance.

III. SCIENTIFIC CONTEXT

A. The theater architects

For most of the ancient theaters, the architect is not known. An exception is the oldest part of the theater in Epidaurus, which is believed to have been designed by Polykleitos the Younger (Charitonidou, 1978, p. 38). He is the architect who also built the Tholos at Epidaurus between 360 and 330 B.C.E., a rotunda building that was acclaimed for very high technical perfection (Charitonidou, 1978, pp. 29–34).

The architects responsible for the design of the theaters, like architects in general, were highly educated. In the 5th century B.C.E., the architectural masterpiece of the Parthenon temple on Acropolis in Athens was built, just to put things in perspective. With reference to ancient Greek architects, Vitruvius explains that in addition to geometry, an architect should also possess knowledge about history, philosophy, physiology, music, medicine, law, arts, optics, etc. Here, Vitruvius leans on older Greek texts, and he quotes the mid-4th century B.C.E. architect Pytheos of Priene for claiming that "the architect ought to be more competent in every skill and discipline than those who have simply brought individual arts to a pinnacle of excellence through study and practice" (Vitruvius, 1, 1, 12). However, Vitruvius also realized that an architect could not master all these disciplines: "But those to whom nature has granted such wits, acuity, and good memory that they are fully skilled in geometry, astronomy, music and related disciplines, pass beyond the business of architects and are turned into mathematicians" (Vitruvius, 1, 1, 17). Thus, to follow this trace it is relevant to look into the field of mathematics.

Mathematics in ancient Greece reached an apex in the 4th century B.C.E. A main source of information on the history of Greek geometry including the work of Euklid (c. 325–265 B.C.E.) is attributed to the Greek philosopher Proclus Lycaeus (412–485 C.E.). It is through his writing, referring to books that are now lost, that we know many details of the contributions of ancient mathematicians. It is a fact that mathematics (in a wider meaning than we have today) was blooming in the 4th century B.C.E.

One of the questions raised in the introduction was, how much did the architects know about acoustics? To through some light on this topic, we can rephrase the question: what was the level of ancient Greek knowledge of mathematics and sound propagation?

B. Plato's Academy and mathematics

Plato (c. 430–347 B.C.E.) founded the famous Academy outside Athens around 387 B.C.E. The mosaic in Fig. 7 shows the Academy with a group of men.

Plato was deeply interested in philosophy and all kinds of science. "Plato caused mathematics in general and geometry in particular to make a very great advance, owing to his own zeal for these studies." (Proclus, 1970, p. 66; Lasserre, 1964, p. 39).

Plato gathered a group of the foremost thinkers and scientists in the Greek world. Among them was the mathematician Archytas of Tarentum (c. 430–365 B.C.E.). Archytas wrote a treatise on Harmony, in the beginning of which he explains how previous generations of mathematicians have "handed down to us clear knowledge about the speed of the stars, their risings and settings, and about geometry, arithmetic, and sphaeric, and last, not least, about music" (Lasserre, 1964, p. 21). In other words, mathematics included

FIG. 7. A group of scientists discussing in Plato's Academy. Mosaic from Pompeii, now at the National Archaeological Museum of Naples. Photo: (C) 2006. Sergey Sosnovskiy (https://ancientrome.ru/art/artworken/img.htm?id=2146); licensed under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license (https://creativecommons.org/licenses/by-sa/4.0/).

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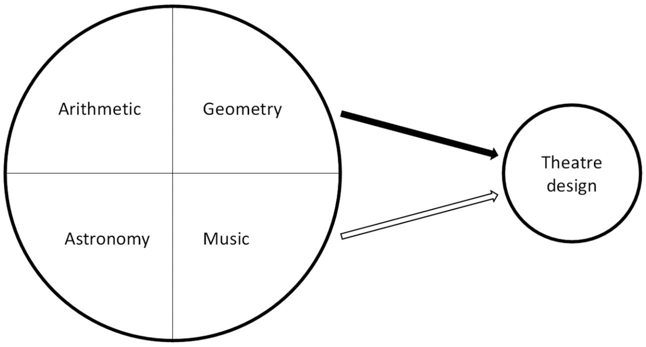

FIG. 8. The four areas of Greek Mathematics and relation to theater design.

not only geometry and arithmetic but also astronomy and music theory. Among these, geometry and music are related to theater design, see Fig. 8. The application of music theory was the background for the sounding vessels in the theaters; an acoustical mistake, as will be discussed later.

A special single-stringed instrument, the *monochord*, was used for the measurement of the frequency of musical sounds (Creese, 2010). Alternatively, the resonating sound when striking vases filled with various amounts of liquid could be used to determine the frequency of musical sound (Lasserre, 1964, p. 172). The connection between music and mathematics is the study of musical intervals.[6] The concept of frequency in relation to the pitch of sound was not known. Instead, they talked about the velocity of movements; "high sounds move themselves more quickly and deep sounds more slowly." (Archytas, Harmony, 47 B 1, Lasserre, 1964, p. 174).

Eudoxus of Cnidus (c. 391–338 B.C.E.) was a remarkable mathematician and a leading scientist, who made many discoveries and wrote books on astronomy and geometry. There is contradicting information about his year of birth and death, 20 years earlier or later, but here we follow Lasserre (Lasserre, 1964, p. 86). Eudoxus was a pupil of Archytas and he joined Plato's Academy for some time in 368 B.C.E. and again around 350 B.C.E. At the last visit, he had just published his most important discoveries in astronomy and the theory of celestial spheres in the work entitled *On Speeds* (Lasserre, 1964, p. 168). Plato had himself also written about the universe as a hollow sphere with a celestial equator and the ecliptic circle, the Earth in the center and six concentric circles carrying the Moon, the Sun, Venus, Mercury, Mars, and Jupiter. However, Plato's theory was insufficient to explain some observations. In contrast, the more advanced model of Eudoxus allowed adjustments in accordance with observations leading to very accurate results (Lasserre, 1964, pp. 144–152).

Taking a closer look at the mosaic showing Plato's Academy in Fig. 7, the framing with theatrical masks reminds us about the importance of the theater in Greek society in general, but here it is just a decoration. The city of Athens is seen in the distance, and to the left is seen the entrance, above which was inscribed (in Greek), "Let no-one ignorant of geometry enter here."[7] The four lamps on top of the entrance are supposed to symbolize the four branches of mathematics (Fig. 8). On a column behind the men is a sundial, an instrument of high importance at the time.[8] In the foreground is a spherical model, obviously related to the topic being discussed. Therefore, it is suggested that the scene depicted in this mosaic could be Eudoxus visiting the Academy around 350 B.C.E. and explaining his new theory of celestial spheres to the elderly Plato while other members of the academy are listening.[9] The open box in the foreground may have contained the paper roll being hold by Plato. One of the men listening must be Aristotle (384–322 B.C.E.), who was a member of Plato's academy for 20 years until Plato's death 347 B.C.E.

C. Aristotle on sound and hearing

Aristotle is best known for his numerous philosophical treatises that cover the areas of logic, natural sciences, metaphysics, ethics, and politics. Although he wrote in Greek, the works are often referred to by the Latin form of their titles. The treatise *De Anima* (On the Soul) contains a detailed treatment of sound and hearing. Aristotle divided the discussion into three parts: excitation of sound (e.g., by a stroke to a metal object), propagation of sound through the air (or water), and perception in the inner ear.

"Aristotle is explicit on the point: on his account, the intervening air is caused to 'vibrate' (*seiesthai*) by the action of the sounding object. This suggests the following picture: the sounding object 'moves' the surrounding air (or water) by causing it to vibrate; this vibration is then transmitted sequentially from one portion of air (or water) to the next; and this movement is ultimately conveyed to the air walled up inside the ear of the hearer. Crucially, no single portion of the air (or water) needs to travel across the gap between sounding object and hearer for this to occur." (Johnstone, 2013, p. 6).

Aristotle was probably the first to explain sound propagation as a wave phenomenon, and his ideas of the physics of sound and hearing are in good agreement with modern understanding. Figure 9 shows an overview of the lifetime of the Greek scientists discussed in this article.

D. Aristoxenus and the sounding vessels

From an acoustical point of view, one of the most interesting persons of the time was Aristoxenus of Tarentum

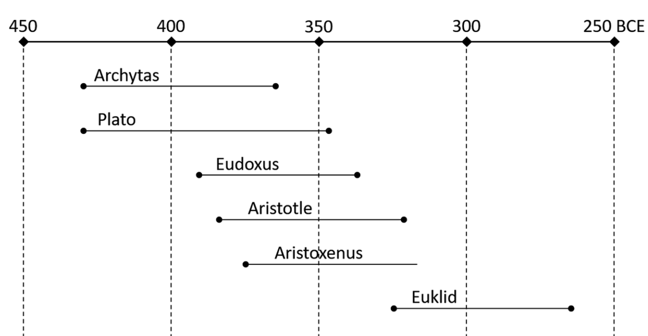

FIG. 9. Important scientists in the 4th century B.C.E. and their lifetime.

(c. 375–fl 321 B.C.E.), who became famous in his own time as "The Musician." He was a pupil of Aristotle, who after the death of Plato had opened his own school of Lyceum in Athens in 336 B.C.E. Aristoxenus wrote a wealth of treatises on philosophy, ethics, and music. His work on music theory is a continuation of the ideas of Archytas (Lasserre, 1964, pp. 183–187; Gibson, 2005). His theory on musical scales was in opposition to the one by Pythagoras (c. 570–495 B.C.E.) which was based on mathematical principles. Aristoxenus claimed that the superior evaluation of musical intervals should be made by the human ear. He said that we evaluate the size of the intervals by the ear and the properties by the brain. In fact, he suggested the equally tempered scale that we use today—more than 2000 years before this scale became generally accepted in the 18th century.

Most of Aristoxenus' work is lost, but from Vitruvius, we know that he became very engaged in the acoustical design of theaters; the idea to install sounding vessels in theaters comes from Aristoxenus. The accurate resonance frequencies and positions of the vessels were stated in a scheme, now lost (Vitruvius, 5, 5, 6).[10] The vessels in the theater are mentioned several times by Vitruvius, first in his Book One: "In theaters, likewise, there the bronze vessels—the ones the Greeks call *echea*—which are enclosed underneath the seats, placed according to mathematical principle based on their pitch." (Vitruvius, 1, 1, 9).

It seems that the idea comes from the association with resonant bodies as used in stringed instruments, and thus Aristoxenus may have thought that the resonating vessels could help amplify the sound in a theater as if the theater were a musical instrument. "For just as musical instruments achieve the clarity of their sounds by means of bronze panels or horn sounding boxes added to the sound of the strings, so, too, the calculations for theaters were established by the ancients on harmonic principles to amplify the voice." (Vitruvius, 5, 3, 8).

One theater where this principle was used, probably for the first time, is in Corinth. Aristoxenus was living in Corinth at the time when the theater was reconstructed and enlarged, around 320 B.C.E., and his work *Elements of Harmony* (Aristoxenus, 1902) dates from the earliest to 321 B.C.E. (Lasserre, 1964, p. 185). Later on, after the conquest and demolition of the city by the Roman general Lucius Mummius in 146 B.C.E., the bronze vessels from the theater were carried to Rome together with other captured treasures (Vitruvius, 5, 5, 8).

However, the idea of amplification by way of these sounding vessels was wrong, which is clear with today's acoustical knowledge. For simple physical reasons, there is no possibility that a vessel can amplify the sound in a theater: the radiated sound power cannot exceed the incident sound power. On the contrary, such vessels can be tuned to absorb sound at a certain resonance frequency (Valière *et al.*, 2013; Rindel, 2013). Already 200 years ago, the physicist and acoustician Ernst F. F. Chladni[11] wrote laconically, "In several theaters, the ancients used sounding vases (vessels) between the seats of the spectators to reinforce the sound, according to Vitruve, but his method did not seem to be of any use." (Chladni, 1809).

The possibility that Aristoxenus was involved in the building of the theater in Corinth, and the fact that he wrote about sounding vessels to improve the acoustics of theaters—referred to with enthusiasm by Vitruvius—could suggest that also other parts of Vitruvius' text about the design of theaters are based on writings by Aristoxenus, now lost.

E. Design rules for theaters

Most of Book Five of Vitruvius' Ten Books on Architecture is devoted to the design of theaters. This is a major source of information about knowledge on this topic in ancient Greece because the text is based on older Greek guidelines. Normally, we think of a theater as a place to watch plays and other performances. It is remarkable, then, that the design guides by Vitruvius only deal with theater acoustics, and not with visual aspects of the theater.

In Vitruvius' texts, the sound of the voice was thought to propagate through the air in a way similar to the waves in water: "It moves by the endless formation of circles, just as endlessly expanding circles of waves are made in standing water if a stone is thrown into it." (Vitruvius, 5, 3, 6). However, sound propagates in three dimensions, and the vertical section must be considered in the theater: "For the voice, therefore, just as for the pattern of waves in water, so long as no obstacle interferes with the first wave, it will not upset the second wave or any of those that follow, all of them will reach the ears of the spectators without echoing, those in the lowermost seats as well as those in the highest." (Vitruvius, 5, 3, 7).

The design of ascending rows of seats must follow a simple geometrical rule: "If a line is extended from the lowest step to the highest, it should touch the edge of every step, that is, every angle. In this way the voice will not be obstructed." (Vitruvius, 5, 3, 4). It is emphasized that this rule must be obeyed also in the case of a horizontal cross-aisle (*diazoma*) (Fig. 10). Although this design rule also helps to ensure good sightlines, unhindered sound propagation is referred to as the reason for the rule. This rule is obeyed in the design of most ancient theaters, whereas it is

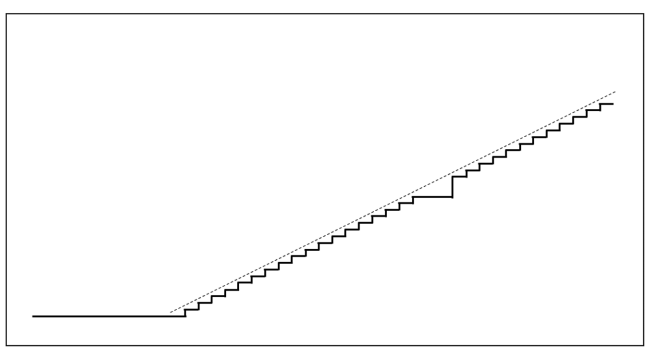

FIG. 10. The geometrical design of ascending seat-rows in the case of a *diazoma* according to Vitruvius. Vertical section. The dotted line extended from the lowest step to the highest.

TABLE I. Size and dimensions of the selected theaters as reconstructed in the models. The capacity is a rounded estimate assuming 2.5 persons per square meter of the horizontal seating area.

Theater	Seat height m	Seat depth m	Seat slope (degrees)	Number of rows	Orchestra shape	Orchestra size m	Audience area m^2	Capacity
Argos	0.32	0.90	19.6	38	Rectangular	20 * 14	919	2300
Thorikos	0.30	0.65	24.8	31	Rectangular	26.7 * 14.3	1028	2600
Kalydon	0.30	0.74	22.1	31	≈Square	15.6 * 14.8	1746	4400
Oeniades	0.38	0.74	27.2	28	Circular	16.1	1299	3200
Iaitas	0.39	0.74	27.8	32	Circular	14.8	1394	3500
Epidaurus phase 1	0.35	0.75	25.0	34	Circular	20.6	1908	4800
Epidaurus phase 2	0.38	0.75	26.9	55	Circular	20.6	3945	9900

often neglected by modern architects, leading to less satisfactory acoustics in modern open-air theaters.

As noted previously, it can be concluded that ancient Greek theaters were designed with high priority for good sound and speech intelligibility. Acoustics as such was not established as a science, but given both textual and architectural evidence, it seems that ancient Greek architects had expert knowledge of mathematics and sound propagation.

IV. THE SELECTED THEATERS FOR THIS STUDY

Six Greek theaters have been selected for the purpose of analyzing acoustics through computer simulations. The accurate dating of the various theaters may be uncertain, but it is believed that this selection of theaters represents theatrical formal development in approximately chronological order: Argos, Thorikos, Kalydon, Oeniades, Iaitas, and Epidaurus. Table I provides an overview of some basic data for the theaters. The estimated capacity is further explained in Sec. VII B. The plans of the six theaters are shown in the same scale for comparison in Fig. 32.

A. Terminology

The terminology of the various parts of Greek theater architecture is as follows (see also Fig. 11):

- *Koilon* (seating area for the audience, same as *cavea* in a Roman theater);
- *Analemmata* (supporting walls at the sides of the *koilon*);
- *Diazoma* (horizontal path, dividing *koilon* into a lower and an upper part);
- *Cunei* (section of audience area between stairways);
- *Prohedria* (special seats for most important people);
- *Orchestra* (area for the dance of the chorus);
- *Skene* (the scene-building);
- *Proskenion* (extension of the scene-building towards the *orchestra*);
- *Paraskenia* (two building structures on either side of the scene-building);
- *Pinnacles* (painted decorations on wooden boards between the columns under the *proskenion*).

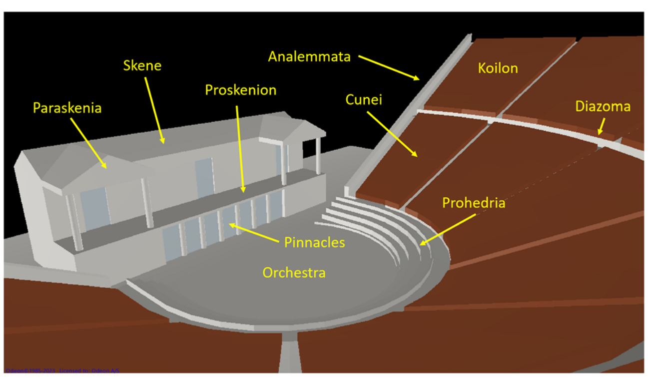

FIG. 11. The terminology of the various parts of Greek theater.

B. Argos

This theater is the earliest one in Argos, dating to the mid-5th century B.C.E. The seats are rectilinear with 38 rows cut into rock. The width of the *koilon* is 20 m at row 1 and 29.5 m at row 23 (Sear, 2006, p. 386, Fig. 136; Frederiksen, 2015, Fig. 1). The total seating area is nearly 1000 m^2. There is no information about a *skene* (scene-building), which may have been a wooden construction, or just a wall if any at all. This theater was chosen to represent the early forerunners before the theater became an entirely architectural construction. In the 2nd century C.E. the seating of this theater was reshaped with curved seating for a Roman *odeum*. Another very large theater was built in Argos around 320 B.C.E.

C. Thorikos

This small theater with a very interesting design is in Thorikos, Attica. The lower part with 19 rows dates from before 425 B.C.E., while the upper part with 12 rows date from the second half of the 4th century B.C.E. The *koilon* is rectilinear in the middle section for about 20 m and curved in both sides, but asymmetrical (Sear, 2006, p. 409; Frederiksen, 2015, Fig. 3). The rectangular *orchestra* is well preserved and bounded by a terrace wall. A small Dionysus temple faces the *orchestra* from one side, and at the opposite side, partly hidden behind the *analemmata*, there are remains of another building (Figs. 12 and 13). There was never an associated scene-building. A very similar layout is assumed for the oldest stage of the Dionysus Eleuthereus Theater in Athens before 460 BCE (Bieber, 1961, p. 57).

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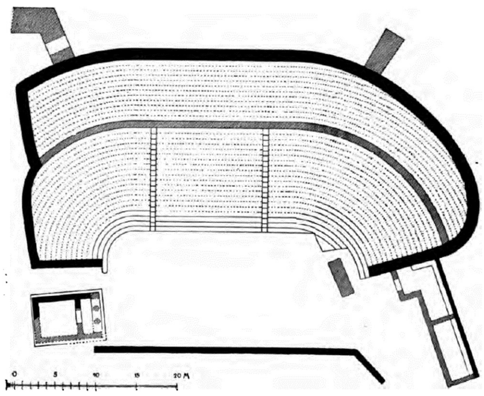

FIG. 12. Plan of the theater of Thorikos. Adapted from (Dörpfeld and Reisch, 1896, Fig. 43).

This theater represents the early formal convention for theaters in which a connection to the temple is obvious.

D. Kalydon

In Aitolia in the Western part of Greece, Kalydon was a prosperous city in the 4th century B.C.E. The theater at Kalydon dates from the late fourth or early third century B.C.E. It is symmetrical with a nearly square *orchestra* (15.6 by 14.8 m) and a Π-shaped *koilon*.[12] The seat-rows of the lower section (rows 1–9) are straight and meet at a right angle between the wings and the central part, whereas the seat-rows of the upper section (rows 10–31) are connected by curved seat-rows in the shape of quarter-circles (Fig. 14). The scene-building had ramps to both sides and the height of the *proskenion* was approximately 2.5 m. Ten half-columns of the Ionic style supported the *proskenion* and were used for the support of *pinnacles*. The sandstones used for the scene-building are like those used for the *koilon*. It is possible that the scene building was added in a later building phase, but still it will be included in the reconstruction applied for the acoustical analysis. The *orchestra* is paved with beaten earth and has a slight slope towards the Southeast corner, probably to drain rainwater (Vikatou *et al.*, 2014; Frederiksen and Vikatou, 2022). In collaboration with the archaeologists, this author previously published an acoustical analysis (Rindel *et al.*, 2018; Rindel, 2022).

FIG. 13. The theater of Thorikos. Photo courtesy of Per Ole Rindel 2018.

FIG. 14. The theater of Kalydon during excavation. Photo by author 2011.

E. Oeniades

The ancient city of Oeniades is in Aitoloakarnia in the Western part of Greece, not far from Kalydon. The theater dates from the 4th century B.C.E. The *koilon* is divided into eleven parts (*cunei*) by stairways. It has a circular shape covering more than 180°, and thus the *analemmata* are not parallel to the scene-building. There has originally been 27 seat-rows, either cut into rock or built with limestone blocks (Sear, 2006, p. 414; Kolonas, 2009, pp. 10–12).

The *orchestra* has an inner diameter of 16.1 m and is paved with beaten earth. It is surrounded by a pathway and a drainage channel, covered by limestone plaques (Figs. 15 and 16). The scene-building of the 4th century B.C.E. was probably a single floor with five large openings in the facade bounded by four pillars of Doric type, providing support for *pinnacles*. In the first half of the 3rd century B.C.E., a *proskenion* was added, and two *paraskenia* were added on either side (phase 2). However, for the following acoustical analysis, the single-floor scene-building of phase 1 is applied.

The geometry of this theater is interesting because the center of the *orchestra* is not the same as the center of the seat-rows; the latter is located somewhat closer to the scene-building such that the circle defining the first row of seats touches the facade of the scene-building (phase 1). Furthermore, the directions of the stairways meet at a point that is different from both centers and even closer to the scene-building. These details in the design suggest that the focus for the audience is not the center of the *orchestra*, but some point closer to the scene-building. Without acoustical analyses is not clear to what extent this horseshoe-shape affects the acoustics. A very similar, not concentric design is found in the theater of Dionysus Eleuthereus in Athens,

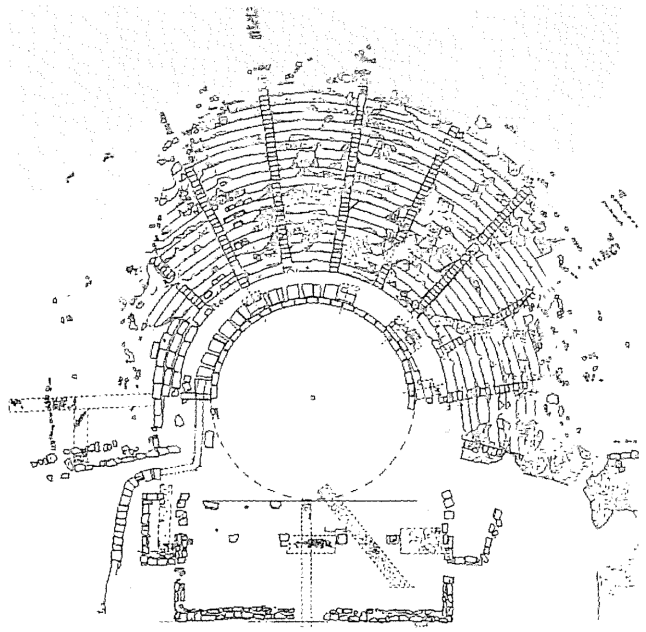

FIG. 15. Plan of the theater of Oeniades. Adapted from (Kolonas 2009, Fig. 9). Courtesy of Ministry of Culture. Hellenic Organization of Cultural Resources Development.

finished probably around 320 B.C.E. (Papastamati-von Moock, 2014, p. 73).

F. Iaitas

This theater is located in Sicily, and dates from the 4th century B.C.E. A newer scene-building dates from around 200 B.C.E. The *koilon* is divided into seven *cunei* by stairways in a U-shape, namely, a semicircle of 180° with small rectilinear extensions beyond the diameter (Figs. 17 and 18). The *analemmata* are parallel to the scene-building. The center of the *orchestra* is also the center of the semicircular *koilon*. A *diazoma* divides the seat-rows into two with 15 rows below and 17 rows above. The *orchestra* has an inner diameter of 14.8 m and is paved in beaten earth. It is surrounded

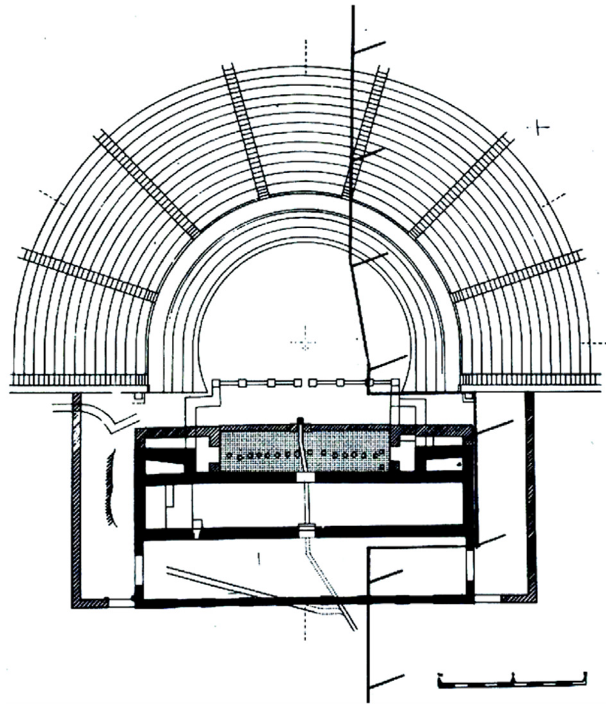

FIG. 17. Plan of the theater of Iaitas. Adapted from (Isler, 1981, Fig. 3). Courtesy of Numismatica e antichità classiche—Quaberni Ticinesi.

by three steps of *prohedria* and a passageway (Sear, 2006, p. 188; Mitens, 1988, pp. 96–98).

G. Epidaurus

This famous theater is in Argolis on Peloponnese. The first phase of the theater with 34 rows of seats divided into 12 *cunei*, and the *proskenion* is probably from around 300 B.C.E., or possible as early as 340 B.C.E. (Sear, 2006, p. 397). The *koilon* has a circular shape covering more than 180°, and thus the *analemmata* are not parallel to the scene-building. The curve of the extreme seat sections flattens and can be described by circles with centers about 3 m on either side of the *orchestra* center. The *orchestra* has an inner

FIG. 16. The theater of Oeniades. Photo by author 2011.

FIG. 18. The theater of Iaitas, Sicily. Photo, Thomas G. Hines 2004 (https://ancienttheatrearchive.com/theatre/iaitas-modern-monte-iato-italy/); licensed under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license (https://creativecommons.org/licenses/by-sa/4.0/).

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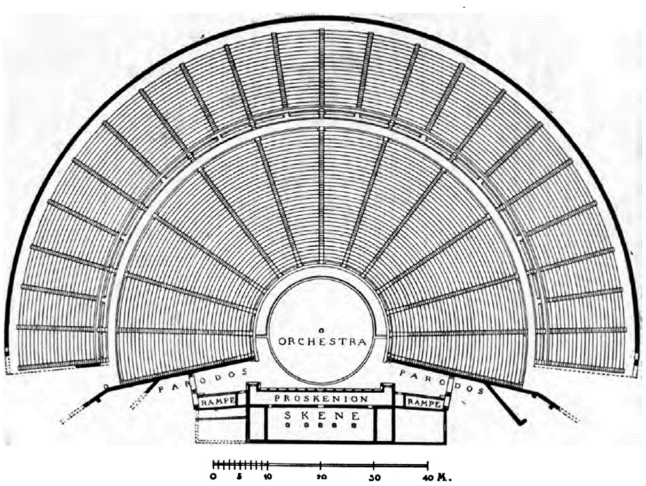

FIG. 19. Plan of the theater of Epidaurus. Adapted from Dörpfeld and Reisch (1896, Fig. 50).

diameter of 20.6 m and is paved in stone. It is surrounded by a passage with a covered drain for rainwater, so the diameter for the first row of seats is 24.6 m (Fig. 19). The seats are cut from stone and have an advanced profile with a front niche for the legs and the front part of the seat a little elevated, as may be seen in the photo (Fig. 20).

A second building phase in early second century BCE added another 21 rows of seats divided into 22 *cunei*. Thus, the audience area was more than doubled from 1910 to 4340 m^2. Concerning the *proskenion*, it may also be from the second building phase. Both the initial smaller size of the theater (phase 1) and the later complete version are applied for the acoustical analysis, and the *proskenion* is included in both versions.

V. SOUND SOURCES IN THE GREEK THEATER

Before detailing the acoustical simulations of these theaters, it is important to consider the historical and archaeological knowledge of performed sound in ancient Greek theater. Sound sources of relevance for the theater are

FIG. 20. The theater of Epidaurus. Photo by author 2011.

TABLE II. Spectrum and A-weighted level of a very loud voice as applied in the acoustical simulations to represent ideal theatrical speech.

	Frequency (Hz)								
	63	125	250	500	1000	2000	4000	8000	A-weighted
SPL at 1 m, dB	39.7	50.7	62.2	72.2	77.9	73.0	65.8	54.9	80.0
Sound power level, dB	49.4	60.4	70.5	81.4	86.7	79.8	72.3	61.5	88.3

chorus singing, musical instruments, and actors performing in tragedy or comedy.

An obvious sound source is the song of the chorus performing in the orchestra. The present study assumes that the intelligibility of this singing had lower priority than that of the spoken words of the actors. Different source positions on the orchestra will be used for the acoustical simulations, but only with a speech source.

A. Speech

According to Vitruvius, the spoken word had the highest priority in the theater. In the acoustical simulations for this study, only the voice of an actor was used as the sound source. We infer that actors performing in the theater were trained to speak in a very loud voice with clear pronunciation of words. Thus, for the acoustical simulations, the vocal effort is set between "loud" and "shouted" as defined in ANSI 3.5 (ANSI, 1997). The spectrum of the source per octave band is given in Table II. The A-weighted sound pressure level (SPL) is 80 dB at 1 m in from of the mouth. The directivity of the sound source is modelled with the data from Chu and Warnock (2002). With a known directivity pattern, it is possible also to specify the sound power level produced by the source (Table II).

B. Source position

The next question is that of the position of the sound source in the theater. Vitruvius explains the difference from the later Roman theater by saying: "the Greeks have a broader orchestra, a more recessed scene-building, and a shallower platform. This they call the *logeion* ('place of words') because on it the tragic and comic actors play their parts while the other artists participate in the production from the orchestra" (Vitruvius, 5, 7, 1).

However, Dörpfeld and Reisch (1896) questioned the validity of the information from Vitruvius, and with reference to archaeological evidence, they claimed that the actors were performing on the *orchestra* in front of the *proskenion*. Since then, there has been some debate among Classical scholars, as to whether the actors were performing on the elevated *proskenion* or in front of the *proskenion* on the level of the *orchestra*. Vases from the time have often decorations that show theatrical scenes, and many of them show the performance on an elevated scene. However, it is also seen very often that there is a stairway (temporary) connecting the

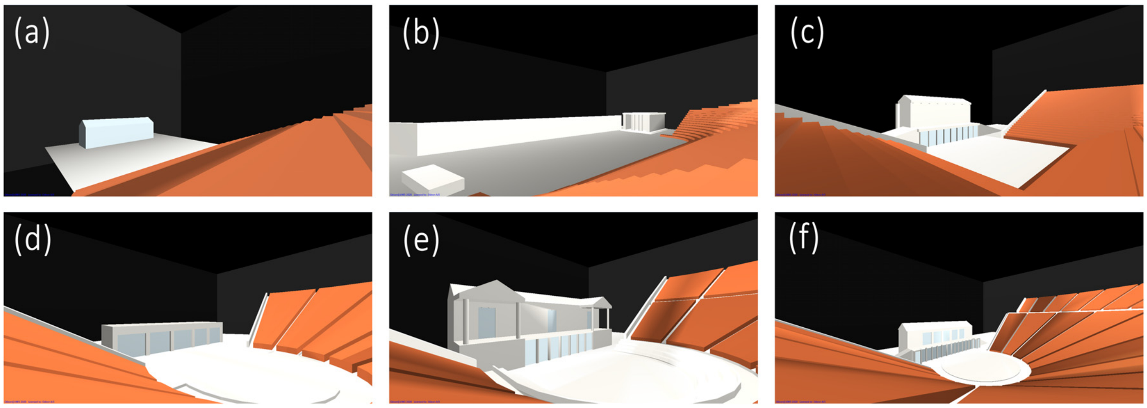

FIG. 21. A 3D view of theater models: (a) Argos, (b) Thorikos, (c) Kalydon, (d) Oeniades, (e) Iaitas, and (f) Epidaurus (phase 2).

orchestra and the *proskenion*, so the actors could easily move up and down between different positions. In some plays, an actor could appear elevated on the roof of the scene-building, and sometimes an actor could suddenly appear or disappear in the middle of the *orchestra*, if the theater had a subterranean passage connected to the scene-building. Therefore, it can be concluded that the position of the actors was not fixed; they could use many different positions.

VI. ACOUSTICAL SIMULATIONS

A. Theater models

Acoustical simulations of the selected Greek theaters were made with the room acoustic software ODEON version 17.03. Three-dimensional views of the computer models of reconstructed theaters are shown in Fig. 21. Plan drawings of the theaters in the same scale are shown in Fig. 32.

B. Source positions

The following four sound source positions have been chosen for the acoustical simulations:

- Position A. In front of the *orchestra*, about 2 m from the edge of the *orchestra*.
- Position B. In the center of the *orchestra*.
- Position C. In the back of the *orchestra*, about 2 m in front of the *proskenion* (or another reflecting wall).
- Position D. Elevated on the *proskenion*, if any (some of the oldest theaters did not have a *proskenion*).

The height of the sound source is in all cases 1.5 m above the floor/ground, approximating the position of the mouth of a standing performer.

C. Materials

The acoustical properties of the materials used in ancient Greek theater construction are simple. The reflective surfaces are either very reflective (stone, beaten earth) or wooden panels with low-frequency absorption. The audience is modelled with relatively high absorption corresponding to a modern audience seated on hard chairs (Table III). The scattering coefficient[13] at mid-frequencies is set to 0.70 for the audience and 0.01 for all other surfaces.

The acoustical simulations are made with full audience, i.e., the situation the theaters were meant for. Although acoustical measurements are often performed in empty theaters for practical reasons, and interesting diffraction effects can appear from the empty seat rows, it is found that the empty theaters are not relevant for the current study.

D. Calculation parameters

ODEON is a room acoustics simulation software program that uses a hybrid calculation method based on geometrical acoustics. The same calculation parameters were used in all the theater models. Raytracing was made with 200 000 rays, which is enough to ensure stable results. The transition order was 2, which means that first- and second-order acoustical reflections were calculated with an image-source method, while higher-order reflections were calculated using a combined raytracing and radiosity method. The duration of the calculated impulse responses was set to 1000 ms.

E. Analysis of early reflections

The early reflections are analyzed in the longitudinal section for each of the four selected source positions

TABLE III. Sound absorption coefficients applied for the acoustical simulations.

	Frequency (Hz)							
Material	63	125	250	500	1000	2000	4000	8000
Beaten earth or stone	0.02	0.02	0.03	0.03	0.03	0.04	0.07	0.07
Wooden panel or door	0.18	0.18	0.12	0.10	0.09	0.08	0.07	0.07
Audience	0.16	0.16	0.24	0.56	0.69	0.81	0.78	0.78

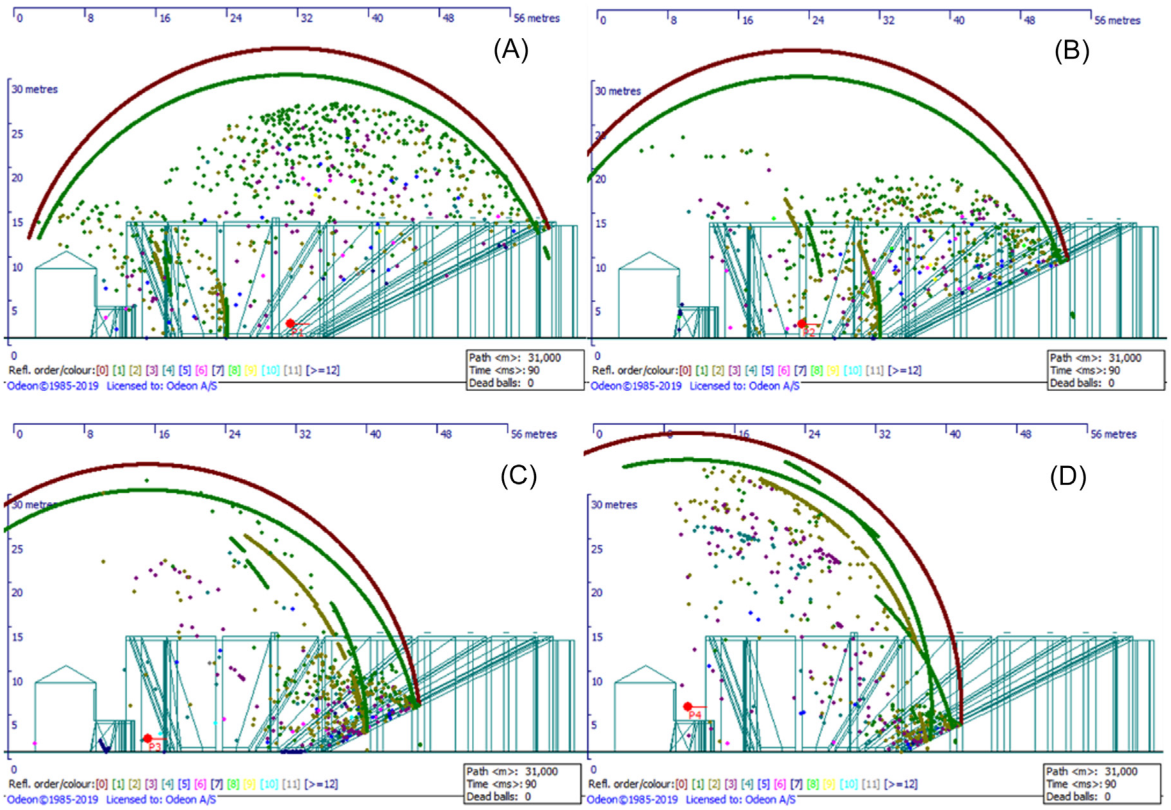

FIG. 22. Longitudinal section of the Epidaurus theater (phase 1) with simulated sound waves propagating from each of the source positions A, B, C, and D. The direct sound has propagated 31 m (dark red wave front). The first-order reflections are shown in green color and the second order reflections in khaki green color. Higher order reflections have other colors.

(Fig. 22). The Epidaurus theater in phase 1 is used as a representative example for this analysis. The theater is seen in a longitudinal section, and a sound wave is simulated in the computer model by many balls emitted by the source and propagating in the vertical plane. Thus, the wave front is seen as a circle, the radius of which expands with the speed of sound. Due to the reflecting objects, the sound wave is reflected or scattered. In Fig. 22, the simulation is stopped when the sound has propagated 31 m. In all the shown cases, the sound wave reflected from the *orchestra* follows closely after the first, direct sound wave. However, in source positions A and B, the sound reflections from the scene-building are much delayed. This contrasts with the source positions C and D, where all the reflections are relatively close together.

In Fig. 23, the sound reflections are analyzed in some detail, and a receiver position in the middle of the theater at the last row is chosen for this analysis. The reflection from the *orchestra* arrives with a short delay time (less than 10 ms), which means that the reflection is beneficial and contributes to the loudness and clarity of the sound. This is the case for all source positions. Other reflections are due to the scene-building and the wooden panels covering the front of the *proskenion*, and these reflections may be either beneficial or disturbing of clarity/intelligibility, depending on the distance of the source from the scene-building. In source positions A and B, the delay of these reflections exceeds 50 ms, which means that an echo is heard. This decreases speech intelligibility and should be avoided. If the distance from the source to the *proskenion* wall is less than 8.5 m, the delay of the reflection is below 50 ms, and no echo is heard. This is the case in source positions C and D.

Another acoustical issue that must have been known to the ancient Greek architects is the attenuation of sound propagating over the audience. This attenuation is similar to that experienced when both a sound source and a receiver (listener) are located close to a soft surface like a grass field. If either the source or the receiver is elevated, the sound attenuation disappears, and the sound is heard louder. Enough elevation corresponds approximately to the grazing angle $\varepsilon \geq 5^\circ$ (Kuttruff, 2017, p. 238). In the theater, the sound-absorbing surface is the audience sitting in the *koilon*. This surface is not horizontal but has an elevation angle α (the slope of the seat-rows), see Fig. 24. This means that the sound propagation can easily be improved by moving the source backwards. This increases the distance d from the first seat-row, and the grazing angle is also increased.

With reference to the symbols in Fig. 24, the grazing angle ε of the sound reflected from the *orchestra* is calculated from the following equation:

$$\tan(\alpha - \varepsilon) = \frac{h}{x} = \frac{H + h}{d + L}. \quad (1)$$

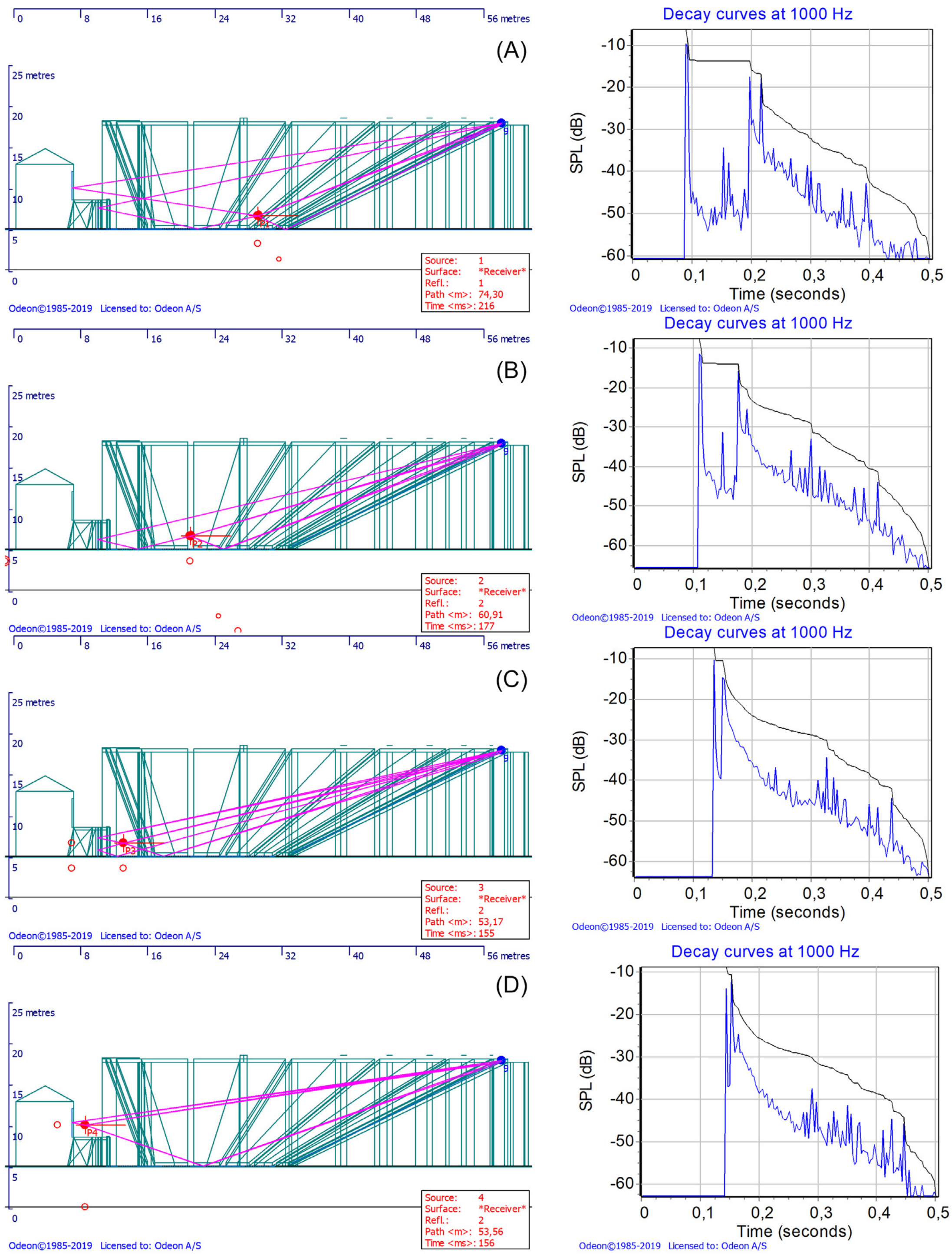

FIG. 23. Analysis of early sound reflections in longitudinal section of the Epidaurus theater (phase 1). From top to bottom, source positions A, B, C, and D. Left, reflection paths. Right, calculated squared impulse responses and decay curves at 1 kHz.

Here, h is the height of the source above the *orchestra*, and H is the height of the receiver on the last row; d and L are the corresponding horizontal distances.

Table IV shows the calculated slope angle and grazing angle for each of the analyzed theaters. Source position A is discarded because the grazing angle would be zero or negative, and thus this position is not usable. In all theaters, the highest value of the grazing angle is obtained with source position C, in the back of the *orchestra* ($\varepsilon \geq 5^\circ$ in Thorikos, Oeniades and Epidaurus, $\varepsilon \geq 2.5^\circ$ in the other theaters). Source position D on the elevated *proskenion* is also good ($\varepsilon \geq 5^\circ$) in Oeniades and Epidaurus, but not as good as position C.

Today, a common rule-of thumb for acoustical design of an auditorium is, that the direct sound coming from the source S should have a minimum grazing angle in order to

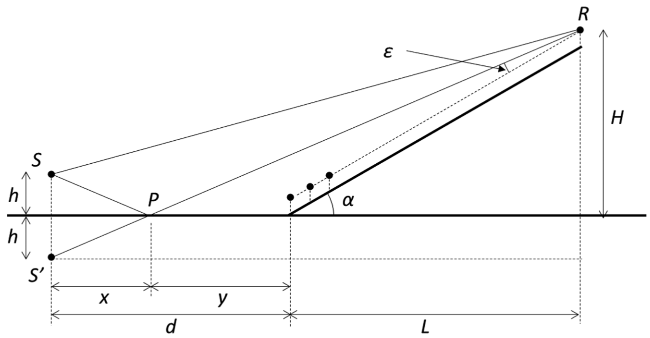

FIG. 24. Geometrical analysis of the sound reflection from the *orchestra*. Source, S; image source, S'; receiver, R; and reflection point, P. The grazing angle is ε.

avoid attenuation of the direct sound. However, the ancient Greek architects wanted the reflection from the *orchestra* to contribute efficiently, which means that the rule of the minimum grazing angle should be applied not to the direct sound, but to the reflected sound coming from the image source S' (Fig. 24). Maybe the secret behind the acoustical success of the ancient Greek theaters is as simple as this. This is also a conclusion from the work of Canac (1967).

F. Acoustical parameters for simulations

Today we usually characterize the acoustics of performance spaces by the reverberation time and a handful of other acoustical parameters defined in ISO 3382-1 (ISO, 2009). These parameters refer to an omnidirectional sound source with a spectrum, that does not vary much from one octave band to the next. However, these parameters have been derived with closed spaces in mind, and it is not obvious that the same parameters are meaningful in an open-air theater like those we are dealing with here (Rindel, 2023). In particular, it is found that the reverberation parameters are not meaningful in this context.

In an open-air theater designed for speech, the obvious acoustical requirement is that the sound perceived by the audience should be loud and clear without disturbing echoes. Concerning the level of sound and clarity, the relevant ISO parameters are the sound strength G and the definition D_{50}.

The sound strength parameter G in dB is the SPL relative to the SPL in a distance of 10 m in a free field, i.e., *without* any sound reflections. The SPL is derived by integration of the total energy in the squared impulse response. The sound strength can be measured or calculated in a simulation. However, using acoustical simulations it is possible to evaluate the level of sound directly by using a realistic sound source. For this purpose, the A-weighted SPL from a source can be used which has sound power, spectrum, and directivity as very loud speech (see Table II). The simulation results with this source can be compared with preferred listening levels for speech communication. This is found to be within the range from 50 to 55 dB when ambient noise is not more than 40 dB A-weighted (Van Heusden *et al.*, 1979). This range includes a 3–5 dB higher listening level that is needed when listening to a language that is not the listener's mother tongue.

The perceived clarity of speech can be expressed by the acoustical parameter D_{50}, defined as the ratio of early energy before 50 ms and total energy. It can take values between 0 and 1, and in an outdoor scenario the D_{50} is typically close to 1. It is also possible to relate the results to intelligibility ratings (Rindel, 2023, see Table II). Thus, $D_{50} \geq 0.55$ is rated as "good," and $D_{50} \geq 0.80$ is "excellent." Another measure that is often used for speech clarity is the speech transmission index (STI), which is defined in IEC 60268-16 (IEC, 2011). However, STI is found to be misleading in relation to open-air theaters, because it is completely insensitive to delayed reflections that cause echo problems (Rindel, 2023). For this reason, STI is not used in the present study.

Since echo can be an issue in open-air theaters, the echo strength by Dietsch and Kraak (1986) is found to be relevant and useful. If the value exceeds unity, there is a high probability of an annoying echo.

A new parameter is the efficiency E in dB, defined as the total sound level in the receiver position relative to the direct sound level in the same position (Rindel, 2023). Thus, for a given source position it is a measure of the amplification of the sound provided by the theater. The efficiency is calculated in octave bands as the total SPL minus the SPL of direct sound in the same position using an omnidirectional sound source. The average of the efficiency in the 500

TABLE IV. Geometrical characteristics of the selected theaters; horizontal dimensions L and d, slope angle α and grazing angle ε of sound reflection from *orchestra* to the last seat-row from three source positions: B (center of *orchestra*), C (in front of *proskenion*), and D (on the *proskenion*).

			Source position B		Source position C		Source position D	
Theater	L (m)	α (°)	d (m)	ε (°)	d (m)	ε (°)	d (m)	ε (°)
Argos	33.3	19.6	8	0.6	13.0	2.5	—	—
Thorikos	20.5	24.8	6.8	2.2	11.0	5.0	—	—
Kalydon	22.6	22.1	7.8	1.0	12.8	3.8	15.7	2.0
Oeniades	20.4	27.2	10.1	4.2	19.1	9.1	22.6	5.7
Iaitas	26.2	27.8	7.4	1.7	11.4	4.1	15.0	2.5
Epidaurus phase 1	24.9	25.0	15.3	5.3	23.3	8.4	27.8	6.3
Epidaurus phase 2	43.1	26.2	15.3	4.5	23.3	6.9	27.8	5.5

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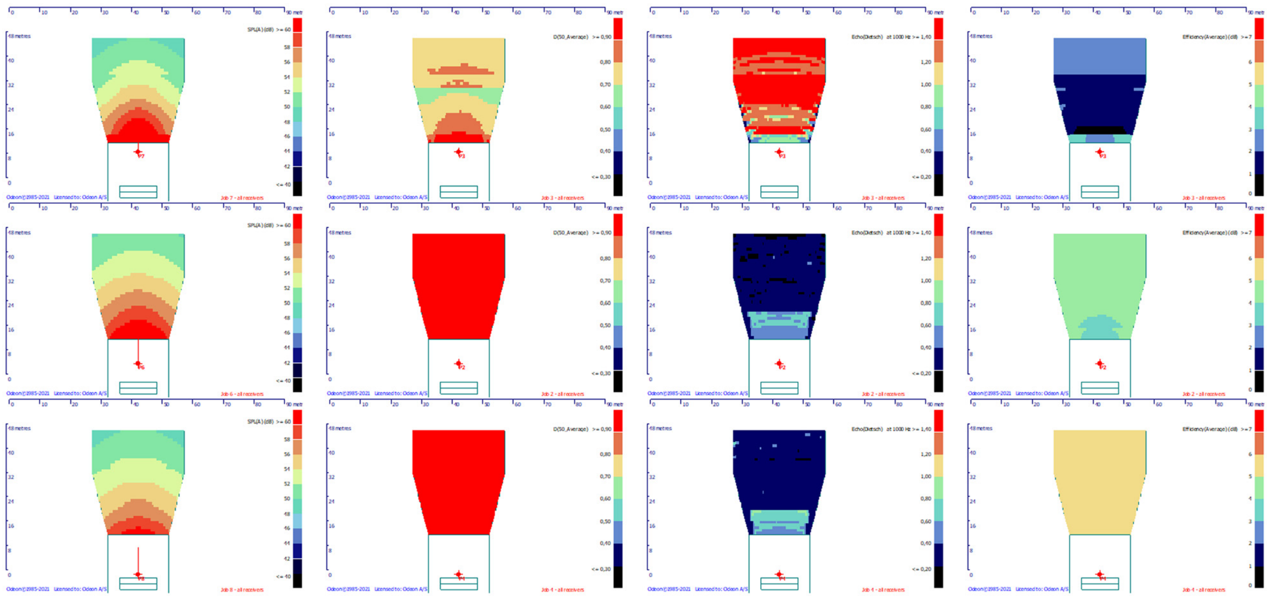

FIG. 25. Grid map results for Argos theater. From left to right, A-weighted SPL of loud speech, D_{50}, echo strength, and efficiency. Top to bottom, source positions A, B, and C.

and 1000 Hz bands is used as a single-number value. Efficiency is a measure of the beneficial effect of sound reflections in the theater. In an open-air theater, this parameter can typically take values between 0 and 9 dB. For example, a reflection from a single, perfectly rigid surface near the sound source doubles the sound energy, which means an efficiency of 3 dB.

G. Results of acoustical simulations

The results of acoustical simulations are shown in Figs. 25–31. The sound source positions A, B, and C are applied in all theaters, as well as position D in those theaters, permitting the possibility of an elevated source on the *proskenion*. The displayed acoustical parameters are the A-weighted SPL of very loud speech, the definition D_{50} (speech clarity), the echo strength, and the efficiency. The former uses the directive sound source as defined in Table II, while the other three parameters use an omni-directional sound source as in measurements according to ISO 3382-1 (ISO, 2009).

Results for the Argos theater (Fig. 25) show that the sound level decreases with distance and is relatively low in the last seat rows. The speech clarity is "Excellent" for

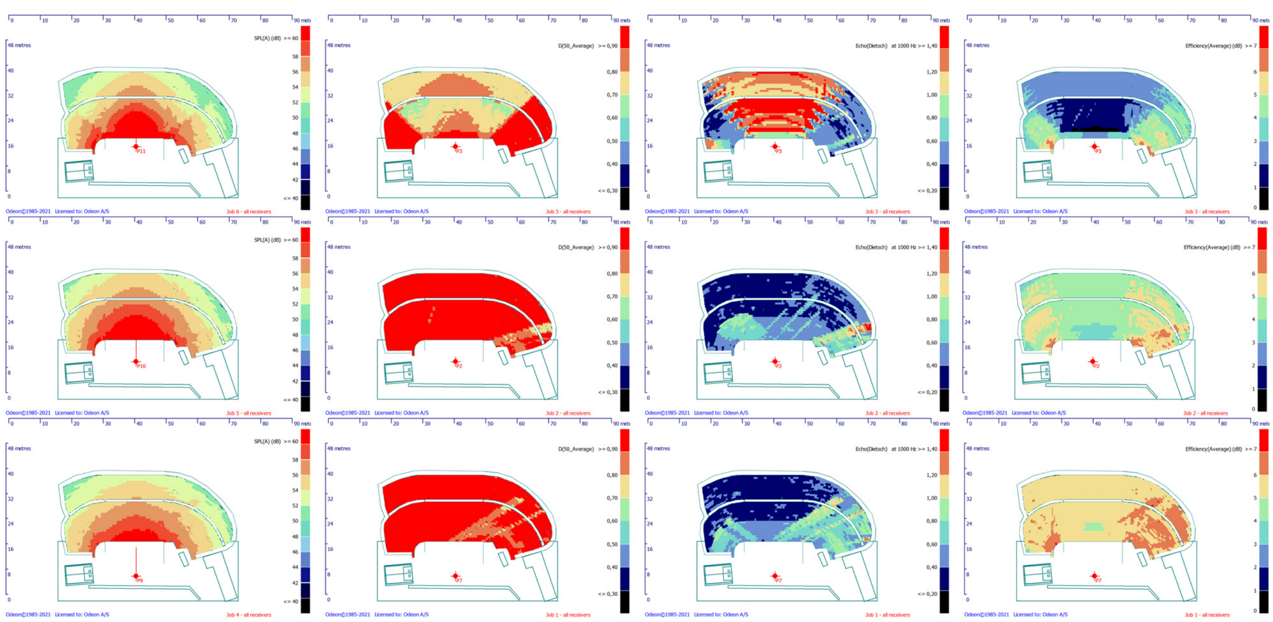

FIG. 26. Grid map results for Thorikos theater. From left to right, A-weighted SPL of loud speech, D_{50}, echo strength, and efficiency. Top to bottom, source positions A, B, and C.

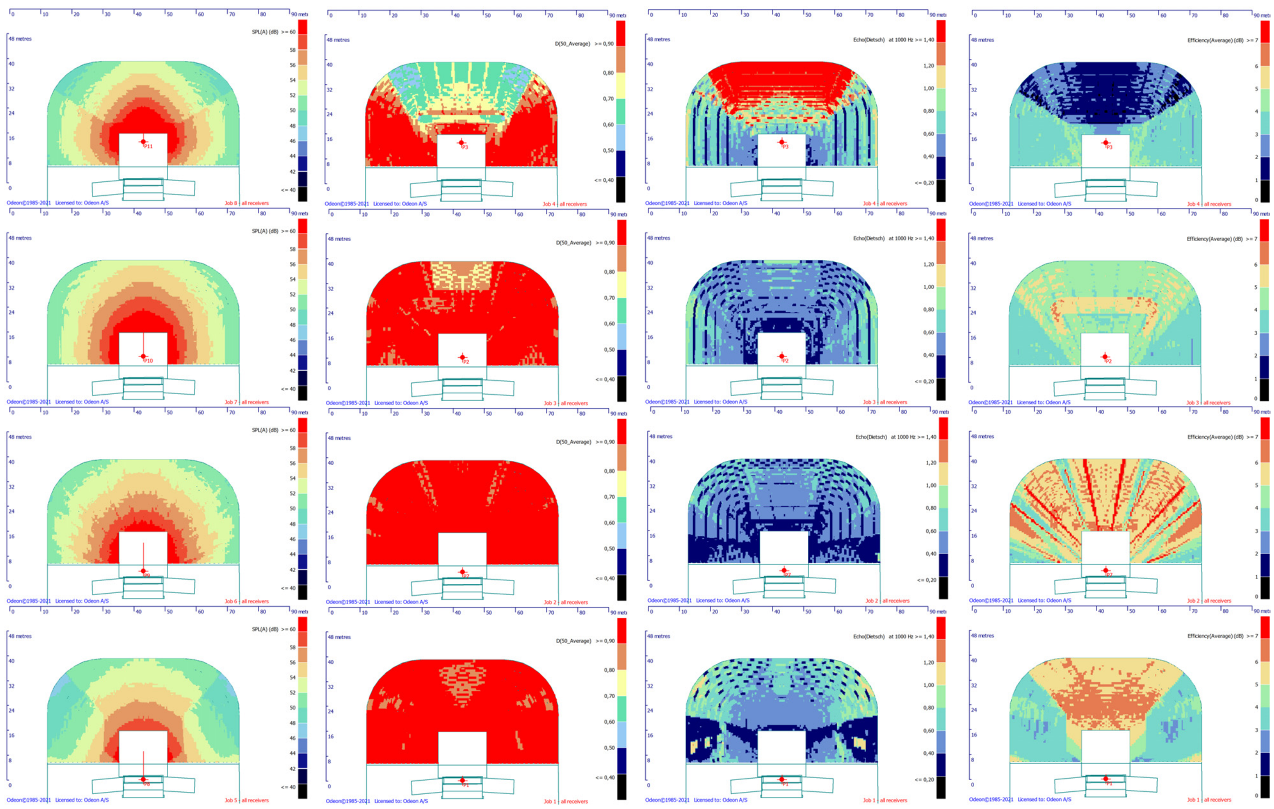

FIG. 27. Grid map results for Kalydon theater. From left to right, A-weighted SPL of loud speech, D_{50}, echo strength, and efficiency. Top to bottom, source positions A, B, C, and D.

source positions B and C, but not for source position A. The echo strength indicates echo problems in all seats with source position A. The efficiency parameter varies with the source position but is very homogeneous over the listener positions. It is poor with source position A, better with position B, and best with position C. In conclusion, source positions B and C are both good.

Results for the Thorikos theater (Fig. 26) show that the sound level is relatively high, even in the last seat rows. The speech clarity is "Excellent" for source positions B and C,

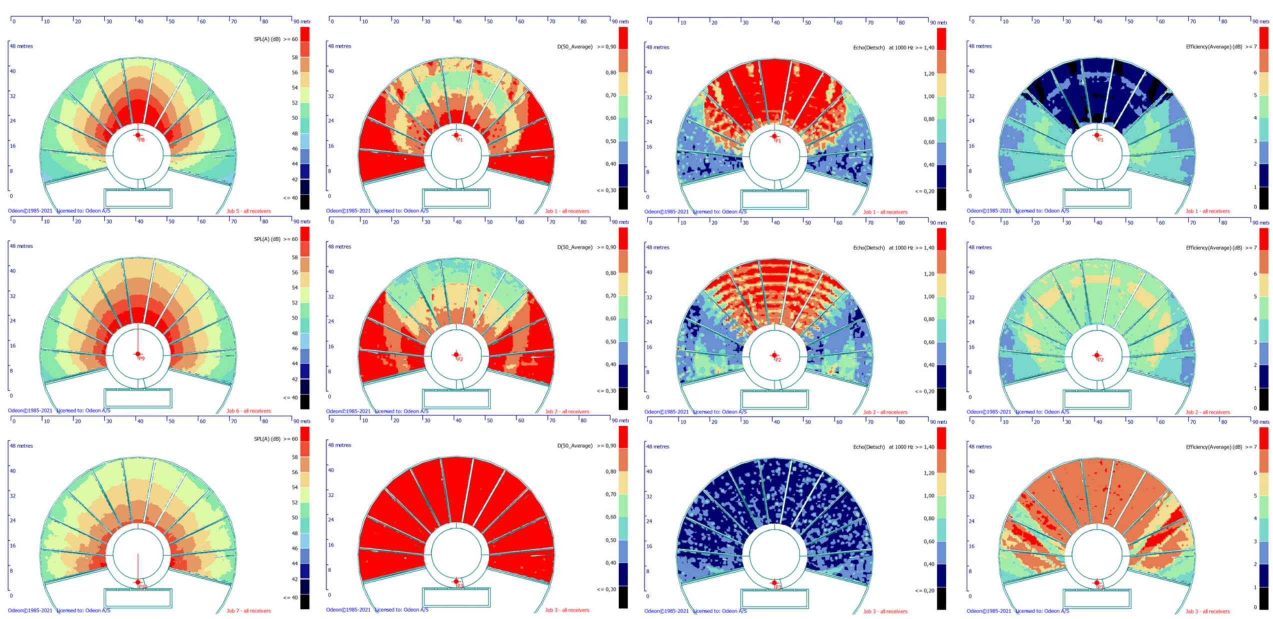

FIG. 28. Grid map results for Oeniades theater. From left to right, A-weighted SPL of loud speech, D_{50}, echo strength, and efficiency. Top to bottom, source positions A, B, and C.

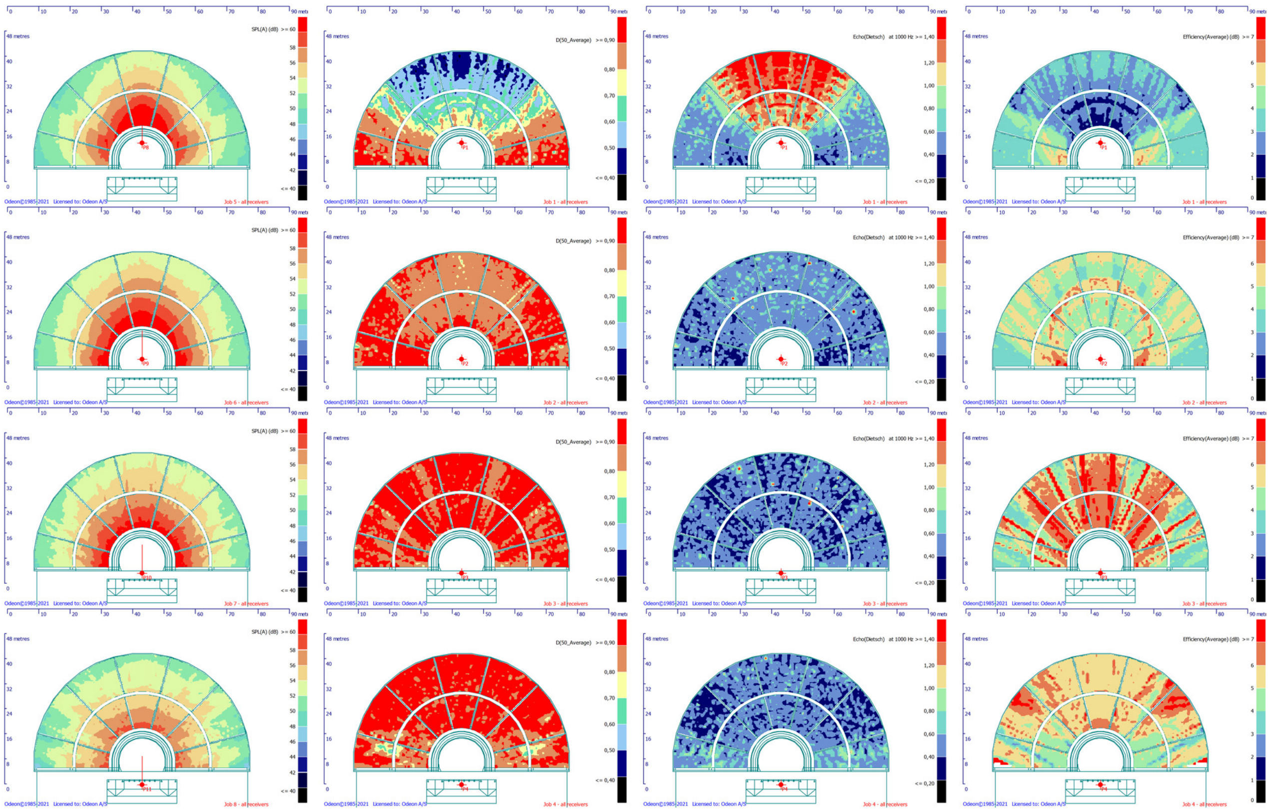

FIG. 29. Grid map results for Iaitas theater. From left to right, A-weighted SPL of loud speech, D_{50}, echo strength, and efficiency. Top to bottom, source positions A, B, C, and D.

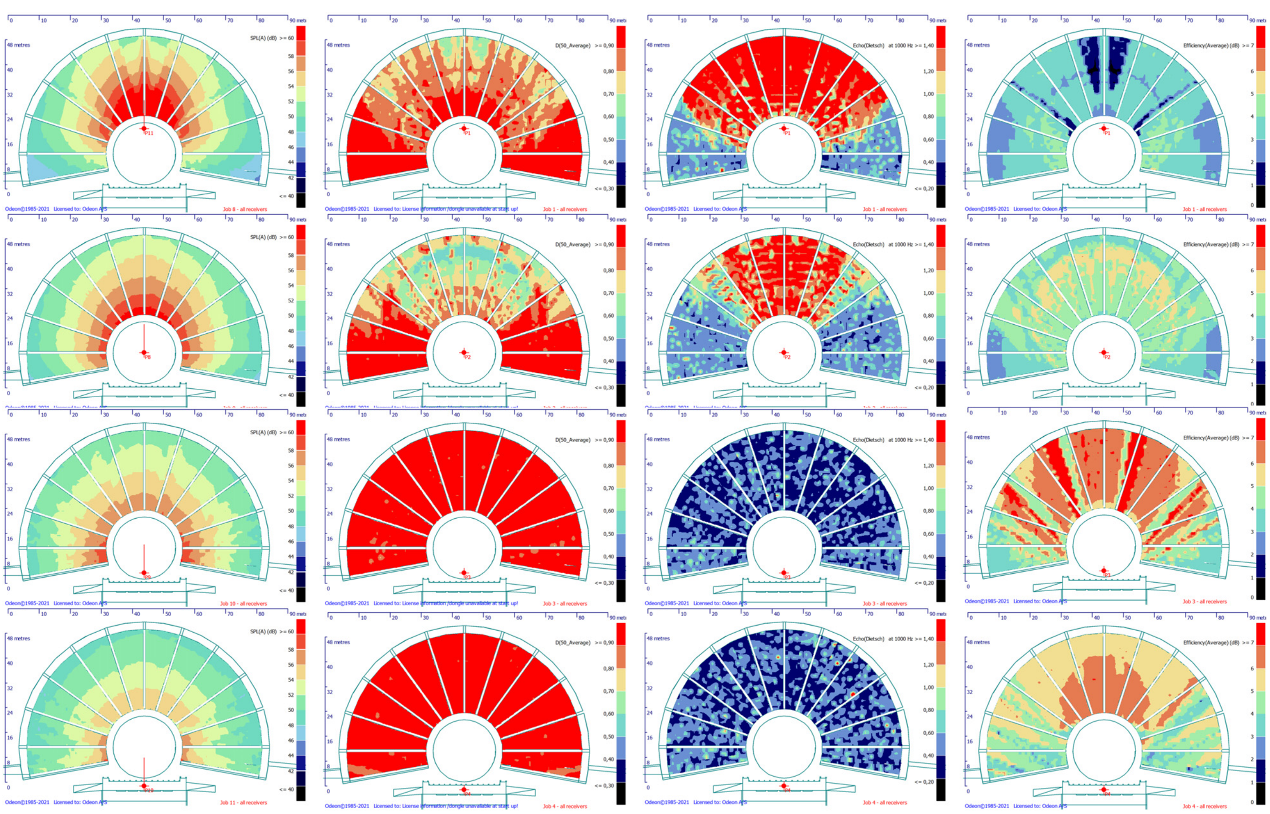

FIG. 30. Grid map results for Epidaurus theater (phase 1). From left to right, A-weighted SPL of loud speech, D_{50}, echo strength, and efficiency. Top to bottom, source positions A, B, C, and D.

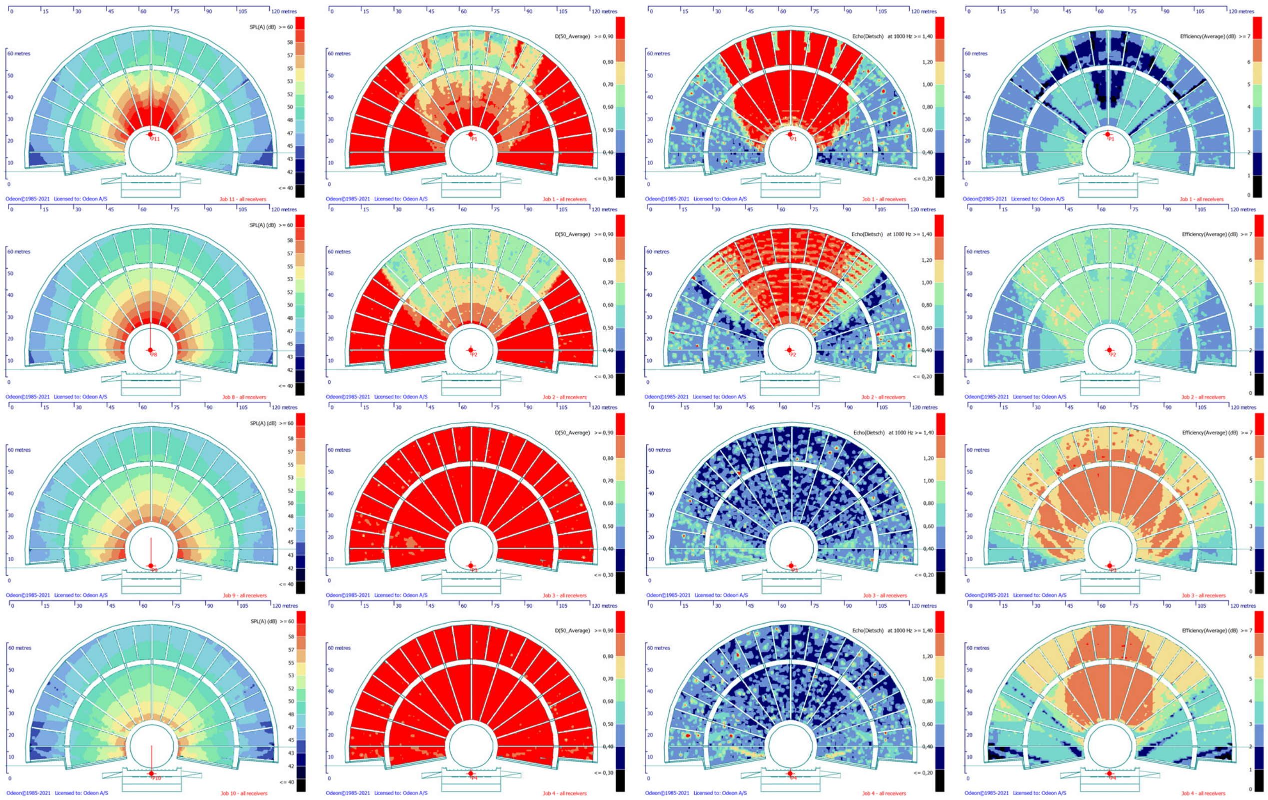

FIG. 31. Grid map results for Epidaurus theater (phase 2). From left to right, A-weighted SPL of loud speech, D_{50}, echo strength, and efficiency. Top to bottom, source position A, B, C, and D.

but not for source position A. The echo strength indicates echo problems in the center seats with source position A. The efficiency parameter varies with the source position and is poor with source position A, better with position B, and best with position C. In conclusion, source positions B and C are both good.

Results for the Kalydon theater (Fig. 27) show that the sound level is quite evenly distributed with source positions B and C, but not with positions A and D. The speech clarity is "Excellent" for all source positions except position A. The echo strength indicates echo problems in the center seats with source position A. The efficiency parameter varies with the source position and is poor with source position A, and best with position C. In conclusion, source position C is the best.

Results for the Oeniades theater (Fig. 28) show that the sound level is quite evenly distributed with source position C, but not with positions A and B. The speech clarity is "Excellent" with source position C, with problems in the center seats with source positions A and B. Very similar results are revealed by the echo strength. The efficiency parameter varies with the source position and is poor with source position A, and best with position C. In conclusion, source position C is the best.

Results for the Iaitas theater (Fig. 29) show that the sound level is quite evenly distributed with source positions B, C, and D. The speech clarity is "Excellent" for all source positions except position A. The echo strength indicates echo problems in the center seats with source position A. The efficiency is best with source positions C and D. In conclusion, all source positions except A are good.

Results for the Epidaurus theater (phase 1) (Fig. 30) show that the sound level is quite evenly distributed with source positions C and D. The speech clarity is "Excellent" for all source positions C and D. The echo strength indicates echo problems in the center seats with source position A and B. The efficiency is best with source positions C and D. In conclusion, source positions C and D are good.

Finally, Fig. 31 shows the results for the Epidaurus theater (phase 2) with the extension of the theater made in the 2nd century B.C.E. The general picture is like that from phase 1, but because of the size of the theater, the SPL in the new part is relatively low. The good acoustics of the old part remain unchanged. It is tempting to imagine that the knowledge of theater acoustics in the 4th century B.C.E. included an idea of the maximum size of a theater, above which the acoustics would be compromised, and that this knowledge was ignored in the following centuries, when much larger theaters became common.

VII. DISCUSSION

A. Importance of sound source position

The acoustical simulations have confirmed the result from the analysis of early reflections in Figs. 22 and 23, namely, that the optimum sound source position in all of the

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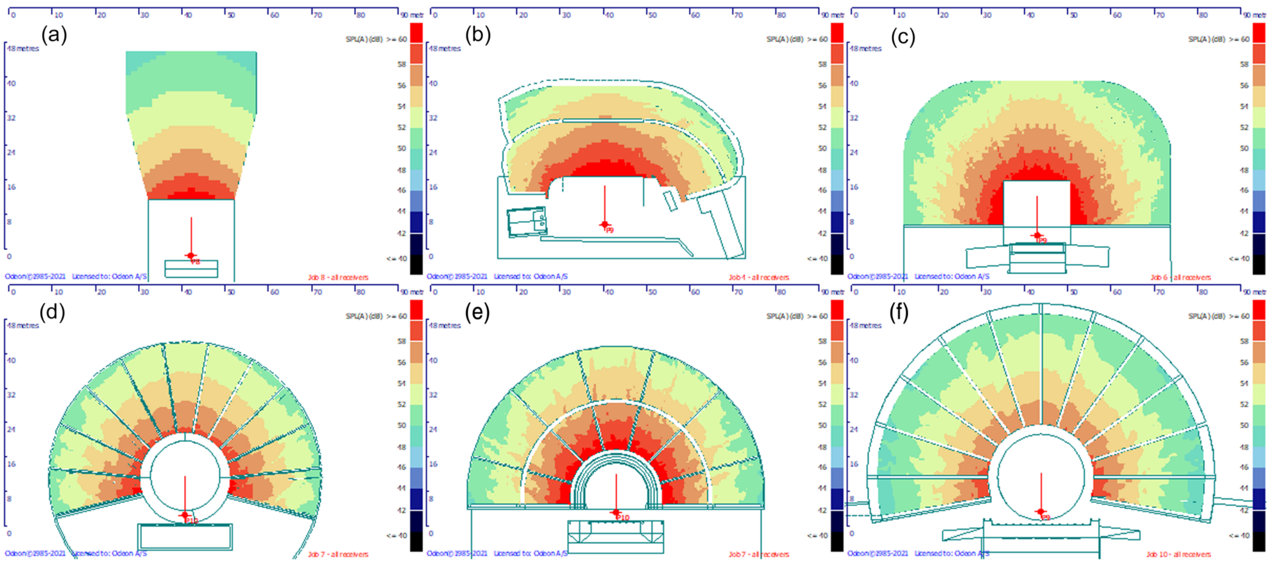

FIG. 32. Calculated A-weighted SPL of very loud speech in six theaters with the speaking person standing in source position C. The theaters are shown in the same scale for comparison. (a) Argos, (b) Thorikos, (c) Kalydon, (d) Oeniades, (e) Iaitas, and (f) Epidaurus phase 1.

selected Greek theaters is on the *orchestra* at a short distance from the *proskenion* (source position C). Echo problems may occur when the source is moved to the center of the *orchestra*, and they become excessive if the source is moved closer to the audience. The echo is due to reflections from the scene-building or the back wall in theaters without a scene-building (Argos, Thorikos, and Oeniades).

In theaters with a scene-building, the elevated source position (D) is not better, but nearly as good as the position in front of the *proskenion*. This result is surprising because it is normally assumed that an elevated source position is beneficial for sound propagation. However, in these theaters, the steep slope angle of the seat-rows means that the direct sound can propagate without any excess attenuation from both source positions C and D, and nothing is gained by elevating the source. In fact, the propagation of the sound reflection from the *orchestra* is better from position C than from the elevated position D; the grazing angle is smaller with source position D (Table IV). As seen in Fig. 23, the reflection point in the *orchestra* is near the source with position C, but far from the source with source position D. The result is that the SPL with source position D is reduced compared to that with source position C (see Figs. 27–31).

It is remarkable that the clarity of speech is excellent in all theaters when using source position C or D.

B. Importance of size

The capacity of the theaters, i.e., *the* maximum number of people in the audience, is often presented in the literature, and sometimes in surprisingly high numbers. The depth of the seat-rows is usually around 0.7 m, and the minimum width for a seated person is from 0.5 to 0.7 m. Therefore, it is realistic to assume between two and three persons per m^2, for a plausible estimate of capacity. However, since there are no well-defined seats in these theaters, capacity can only be an estimate. The horizontal area of the audience area may be a better measure of the size of the theaters see Table I.

The example of the Epidaurus theater phase 2 shows that the size of the theater is very important for the sound level and thus for the quality of the acoustics. In an open-air theater, the SPL will unavoidably decrease with distance. While the six theaters constructed in or before the 4th century B.C.E. have audience areas between approximately 1000 and 2000 m^2, the enlargement of Epidaurus in phase 2 has the audience area increased from 1908 to 3945 m^2.

Figure 32 shows the plan of the six selected theaters in the same scale, for comparison of the size. The results displayed are the calculated A-weighted SPL of very loud speech for each of the theaters with the sound source in position C.

Figure 33 shows the cumulative distribution function of calculated A-weighted SPL of very loud speech for each of the theaters with the sound source in position C. Looking at the median values (the 50% percentiles), SPL varies between 52 and 55 dB in the six old theaters but drops to 49 dB in the much larger Epidaurus phase 2. Thus, the

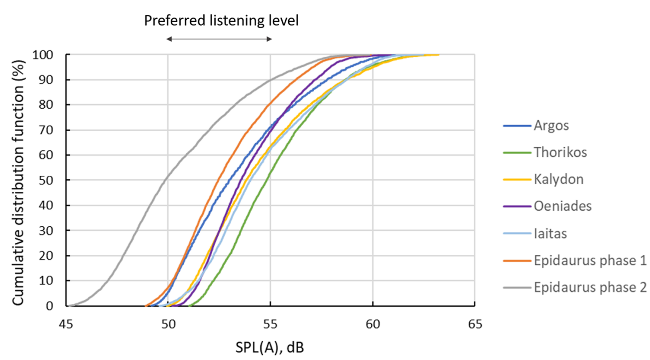

FIG. 33. Cumulative distribution of calculated A-weighted SPL of very loud speech in seven theaters. Source position C.

extension of the theater in the 2nd century B.C.E. was at the expense of the acoustic quality taking the theater as a whole. Of course, the excellent acoustics in the older part (below the *diazoma*) remained unchanged.

C. Importance of orchestra and koilon shape

The shapes of *orchestra* and *koilon* are closely linked. When the *koilon* has a shape like a funnel, the rainwater that concentrates near the *orchestra* is an issue that the ancient architects had to deal with. Thus, a drainage channel is often found between the rim of the *orchestra* and the first seat-row. This means that the distance d is increased, which is beneficial for the unattenuated sound propagation, because the grazing angle of sound reflection from the *orchestra* is increased (see Fig. 24).

If we measure the size of the *orchestra* as the distance from the front of the *proskenion* to the first seat-row, the size varies considerably between the theaters. In Thorikos there is no *proskenion*, but the distance from the back wall to the first seat-row is 14 m. In the theater of Iaitas, the size of the *orchestra* is approximately 14 m, which is close to the size of the square *orchestra* in Kalydon. In the theaters of Oeniades and Epidaurus, the *orchestra* is considerably larger, approximately 21 and 23 m, respectively. The size of the *orchestra* is either around 50 Greek feet or around 75 Greek feet. Acoustically, both sizes work equally well.

The efficiency parameter can give an idea of how well the construction of the theater supports sound propagation throughout. Again, the source position C in the back of the *orchestra* is chosen for the comparison, see Fig. 34. The median values for all source positions are presented in Table V.

Based on the results of the efficiency parameter in Fig. 34 and Table V, the theaters can roughly be divided into two groups: one group without the semicircular *koilon* (Argos, Thorikos, and Kalydon) and another group with the semicircular *koilon* (Oeniades, Iaitas, and Epidaurus 1). In the theaters of Argos and Thorikos, the efficiency with position C is almost constant between 5 and 6 dB. In Kalydon, the efficiency varies much more over the seats, and it is below 5 dB in 25% of the seats and exceeds 6.5 dB in 10% of the seats.

The theaters in the second group have efficiency with position C equal to or better than 6 dB for half the seats, but

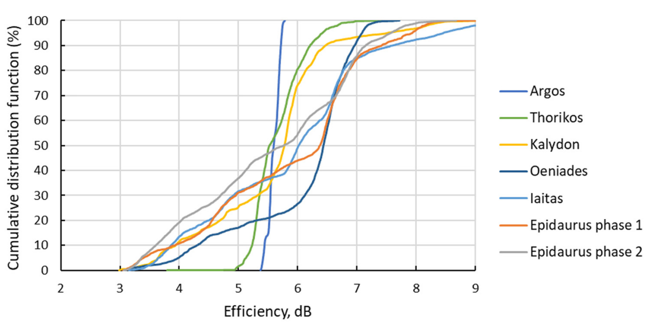

FIG. 34. Cumulative distribution of calculated acoustical efficiency in seven theaters. Source position C.

TABLE V. Median values of the cumulative distribution of calculated acoustical efficiency in dB in seven theaters. Source positions A through D.

	Median value of E, dB			
	Source position			
Theater	A	B	C	D
Argos	1.8	4.7	5.6	—
Thorikos	2.7	4.6	5.5	—
Kalydon	3.0	4.5	5.8	4.9
Oeniades	2.8	4.5	6.4	—
Iaitas	3.1	4.9	6.0	5.5
Epidaurus phase 1	3.4	4.4	6.4	5.4
Epidaurus phase 2	3.1	4.4	5.7	5.7
Average	2.8	4.6	5.9	5.4

at the expense of somewhat lower efficiency in the seats on the sides. However, the efficiency in Epidaurus 2 is clearly lower than that of the smaller, semicircular theaters. These results show the success of the semicircular theater as it was developed in the 4th century B.C.E., but also the problems that arose when the size of the theater increased above an audience area of around 2000 m^2.

The acoustical importance of the source position in a theater is clearly seen in the efficiency results shown in Table V. While the efficiency is high with source positions C and D, it decreases when the source moves away from the scene building, and drops to a much lower value in front of the *orchestra*, position A. In all theaters, the source position C in front of the scene building is the best from an acoustical point of view.

D. Perceived directivity of sound reflections

We shall now take a closer look at the sound that could be perceived by a person seated in the middle of a theater, i.e., *on* the center axis on a row halfway between the first and the last seat-row. Although most sound energy arrives from the frontal direction, namely, the direct sound and the very early reflections from the orchestra and scene-building, there is also some reflected or scattered sound coming from other directions. Especially the sound coming from side directions is interesting, because these arrivals of off-axis reflections may contribute to the quality of the perceived sound. In room acoustics, this effect is called *apparent source width* (ISO 3382-2, A.2.4, ISO, 2008) and can be evaluated with the early lateral energy fraction J_{LF}. It is a similar improvement of sonic perception that is obtained when listening to audio in stereo instead of mono. It is particularly the early lateral energy that contributes to the apparent source width. The early lateral energy fraction J_{LF} is the ratio of lateral energy arriving within 80 ms after the direct sound. It is intended for perception of music in a concert hall, and consequently is takes very low values if applied to an open-air theater.

Figure 35 shows for each of the six theaters, the directional distribution in the horizontal plane of the sound

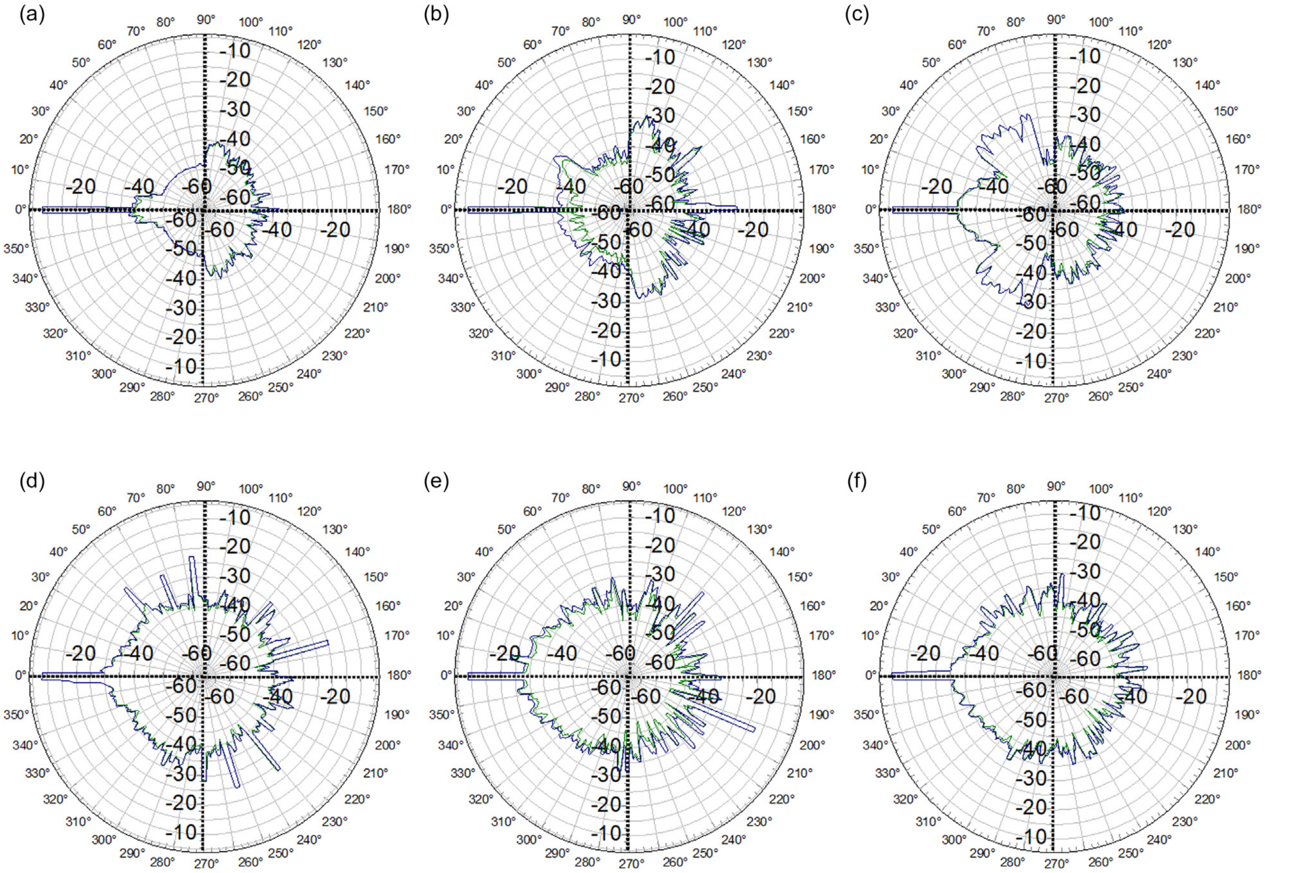

FIG. 35. Directional distribution in the horizontal plane of sound energy arriving from an omnidirectional source in position C to a receiver in the middle of the audience area. The frontal direction is 0°. Green curve, arrival up to 30 ms after direct sound. Blue curve, total energy. (a) Argos, (b) Thorikos, (c) Kalydon, (d) Oeniades, (e) Iaitas, and (f) Epidaurus phase 1.

energy arriving at the receiver from an omnidirectional sound source in position C. This is the optimum source position without echo problems according to the previous analysis. The 500 Hz octave band is chosen, and 3° averaging is applied. Two directional curves are shown: one for the total energy in the impulse response, and another for the energy arriving up to 30 ms after the direct sound. There are very few reflections after 30 ms in any of these theaters. The early lateral energy fraction J_{LF} is very low, around 0.07 in Argos, Thorikos, and Epidaurus phase 1. It is somewhat higher, around 0.10 in Oeniades and Iaitas, and the highest value of 0.14 is reached in Kalydon.

As could be expected, the sound in Argos theater is completely dominated by the frontal sound. In Thorikos theater there are some relatively weak reflections from the direction where the temple is located. In the Kalydon theater, there are very clear early lateral reflections coming from the audience areas on the two sides. The Oeniades, Iaitas, and Epidaurus theaters have directional distributions with relatively strong early lateral energy, evenly distributed from all directions. The conclusion of this analysis is that the Π-shaped *koilon* provides early lateral reflections, but a semicircular *koilon* can further improve the quality of perceived sound, because of evenly distributed early lateral reflections.

VIII. SUMMARY OF ACOUSTICAL FINDINGS

There is evidence from written sources that the ancient architects behind the theaters were aware of the importance of the *orchestra* as a sound reflector, and also the importance of the sound reflection from the surfaces behind the actor, the *pinnacles*. The design of the theater should ensure that speech can be heard loud and clear up to the last seat row. Consequently, the most important acoustic parameters are sound strength G and definition D_{50}. In addition, an echo parameter is very useful, because echo problems can be an issue in open-air settings. Reverberation time and associated parameters, which are important in a closed room, are not meaningful in an open-air theater. The efficiency, which is the level difference between the sound strength and the level of the direct sound, is found to be useful to characterize the overall acoustic support. This depends on the architectural design of the theater and also on the source position in the theater.

Actually, the source position is crucial, because some positions can lead to echo problems, while other positions tend to amplify the sound, at least in the reconstructed theaters with a scene building. Today, the scene building is no longer present in most ancient Greek theaters, and thus the original echo problems are no longer obvious. However, the missing scene building also means that the sound reflections, which made some source positions particularly good, are no longer there.

The six theaters selected for acoustic simulations have comparable sizes, the audience area being approximately 1000 to 2000 m^2. With very loud speech from one of the good source positions, it is found that the majority of the audience will receive a sound pressure level that is within an optimum range for speech communication. The three theaters with a semicircular *koilon* had better acoustic efficiency and more early lateral reflections than the theaters with a different shape of the *koilon*. This supports the earlier findings by Rindel *et al*. (2018) studying the Kalydon theater with a square *orchestra*, that the *orchestra* is more efficient as a sound reflector in a semi-circular theater of comparable size. It is concluded that the architectural development of the theater also led to improved acoustics.

IX. CHANGES IN GREEK THEATER DESIGN AFTER THE 4TH CENTURY BCE

The architecture of the Greek theater developed further during the Hellenistic period (323–31 B.C.E.), mainly by increasing audience capacity by enlarging the *koilon*. Some of the theaters from this period are really huge. As demonstrated in the example of the theater in Epidaurus, increased capacity could be at the cost of excellent acoustics. Since the theaters were open-air spaces, there was no means to avoid a decrease in the average SPL when increasing the average distance from the source to the audience. However, some theaters were built so that the seats near the corners at the sides were left out, i.e., *the* number of seat-rows was greater in the center part of the theater and less in the sides where the acoustics were poor. Examples of this design are the theater of Dionysus in Athens, the large theater in Argos (replacing the old one that was studied here), and the theater in Delos from the 3rd century B.C.E. Although such a design makes sense from an acoustical point of view, the reasons for the special design in these cases may not be acoustical but practical: the theater was built against a hillside, and therefore a complete upper *koilon* of 180° or more would require too great height of the *analemmata* walls.

After the Hellenistic period followed three centuries of the Roman Empire. The Roman theater architecture is different from the Greek and can be divided into three types: (i) the open-air theater with a semicircular orchestra, a high scene front, and a surrounding colonnade, (ii) the smaller roofed theater (*odeum*), and (iii) the amphitheater with spectators surrounding an oval arena. The origin of the amphitheater can be traced to Italy, and the first stone amphitheater was built c. 70 B.C.E. in Pompeii (Welch, 2007). Before that, the *forum* in Italian cities had been used for the purpose: "… from our ancestors we have inherited the custom of giving gladiatorial games in the forum" (Vitruvius 5, 1, 1).

Many Greek theaters were remodeled because the use of theaters had changed. Dancing and singing of a *chorus* were not employed in the Roman theater, and for theatrical performances, the *proskenion* was enlarged and made lower, so the *orchestra* could be used for spectators. This means that the function of the *orchestra* as a sound reflector was neglected or forgotten. Instead, the colonnade behind the audience and the high scene fronts with an overhead reflector contributed to good acoustics. However, the Romans also wanted bloody spectacles with gladiator fights, wild beast hunting (*venationes*), and occasionally the execution of criminals "condemned to the beasts." In the Western part of the Roman Empire including North Africa, amphitheaters were built in large numbers for these purposes, but in the East, very few amphitheaters were built. Instead, the ancient Greek theaters were modified to accommodate these spectacles by removing the first few seat-rows and establishing a kind of arena surrounded by a protecting wall (Sear, 2006, p. 43).

The Roman Emperor Constantine (c. 280–337 C.E.) decided that the Roman Empire should adapt Christianity. After this, the use of the theaters ceased, and many of them were dismantled and used as a source of materials for building churches and other new buildings. The time of the antique theaters was over; they were left as ruins and forgotten for more than a thousand years.

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AUTHOR DECLARATIONS

Conflict of Interest

The author declares that there are no conflicts of interest.

DATA AVAILABILITY

The room models of the analyzed theaters, including calculation results are available for download from the Odeon homepage.[14]

[1]The word "theater" comes from ancient Greek and means a place for viewing. In modern English, the word "amphitheater" is sometimes used for any structure with sloping seating. However, "amphi" means "on both sides" or "around." In the present article "amphitheater" is only used for a Roman structure with an oval or round arena surrounded by seating tiers and originally meant for gladiator fights. Ancient Greek culture did not include "amphitheaters."

[2]References for early Greek theater architecture include Dörpfeld and Reisch (1896), Bieber (1961), Sear (2006), Pappalardo and Borrelli (2007), Moretti (2014), Frederiksen (2015), Anti and Polacco (1969), and Frederiksen (2000).

[3]The length of the Greek foot could vary a little from one place to another: Delphi 0.296 m, Epidaurus 0.302 m, Athens 0.307 m, and Olympia 0.320 m (Maximos and Spathari, 2004, p. 24).
[4]Aristotle: *Problems* 901b30-35 (XI.25). Translated by Hett, W.S., the Loeb Classical Library 1926.
[5]Translations from Latin of Vitruvius here and in the following are by Ingrid D. Rowland.
[6]Mathematicians believed that the reality of sound was inherited in the numbers 6, 8, 9, and 12, which represent the musical intervals of the octave (2:1), the fifth (3:2), the fourth (4:3), and a whole-tone (9:8). In mathematical terms 9 is the arithmetic mean of 6 and 12, while 8 is the harmonic mean of 6 and 12.
[7]According to an unverified story from the time of Proclos.
[8]Several constructions of sundials are mentioned by Vitruvius, one of them called an Arachne, a device invented by Eudoxus. Vitruvius, 9, 8, 1.
[9]If this happened 350 B.C.E., Plato would have been around 80 years, Eudoxus around 40 years, and Aristotle 34 years. A sketch of the celestial-terrestrial model of Eudoxus is shown in Fig. 4, p. 140, of the commentary to Vitruvius (Editors, Rowland and Howe, 2001).
[10]Vitruvius, 5, 5, 6. See also Fig. 82, p. 246 in the commentary to Vitruvius (Editors, Rowland and Howe, 2001).
[11]Ernst Florenz Friedrich Chladni (1756–1827) is known for discovering a method to visualize modal figures on vibrating plates, so-called Chladni figures. He invented musical instruments and was a pioneer in experimental acoustics. He is sometimes referred to as the father of acoustics.
[12]Π is the Greek letter capital Pi.
[13]The scattering coefficient as applied in Odeon is a measure of the degree of scattering of a sound reflection due to the roughness of the surface. This does not depend on the size of the surface, but it is frequency dependent, and the applied number refers to the mid-frequencies, 500–1000 Hz.
[14]Odeon homepage, www.odeon.dk/downloads/odeon-zip-archives. The scattering effect due to the edges of a finite-size surface is handled separately and inherent in the applied scattering model.

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