Chapter 30

Êcheia

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“I am satisfied," said Lord Curryfin, "the art of making these vases is as hopelessly lost as that of making mummies." Miss Niphet encouraged him to persevere. She said: "You have produced a decided resonance: the only thing is to subdue it, which you may perhaps effect by diminishing the number and enlarging the intervals of the vases." He determined to act on the suggestion, and she felt that, for some little time at least, she had kept him out of mischief. But whenever anything was said or sung in the theatre, it was necessary, for the time, to remove the êcheia.

Peacock 1896: 133.

Introduction

Strong early reflections (as are often found in large enclosed buildings with plenty of flat surfaces) can have a devastating effect on the intelligibility of speech as a result of the reflected sound arriving at the listener at slightly different times. It is considered ‘flattering’ for vocal and some instrumental performance. These strong early reflections are not found in Greek and Roman theatres. The great clarity that so many people admire about a Greek or Roman theatre may also be a problem for certain types of performance; the lack of obstruction or reflection assisting with the audibility of speech, but being less flattering for song and other forms of music. A theatre was (and still is) used for multidisciplinary art forms.

But Vitruvius, in Book I of *De Architectura,* claimed further acoustic enhancements could be made:

> In theatres, also, are copper vases and these are placed in chambers under the rows of seats in accordance with mathematical reckoning. The Greeks call them Êcheia. The differences of the sounds which arise are combined into musical symphonies ... it becomes fuller, and reaches the audience with a richer and sweeter note.

Vitruvius, Bk. I Chap I (trans. Granger)

From this, we can deduce that Vitruvius is interpreting an idea that he witnessed and has been passed down by the Greeks. This chapter explores the notion of intent and purpose behind the concept.

So what, exactly, was the problem Vitruvius was attempting to solve? He was aware of an acoustical issue caused by the reflection of sound waves: namely, that interference to the original source is created by reflections making the original less clearly audible or defined. Vitruvius called this reflection of sounds *resonantia*. This differs from our modern day meaning of the word resonance: that is, a common cause of reinforced sound production in acoustic musical instruments (when one sonic object vibrates at the same natural frequency as another, forcing the second object into vibrational motion; also of particular importance in architectural acoustics). Although such reflections were kept to a minimum by the designs of Roman and Greek theatres, the *resonantia* would still have been seen as a considerable problem. If any strong, extraneous reflections come back to a listener at slightly different times, then speech, for example, would have become difficult to understand. As Vitruvius pointed out, an inflected language such as Latin is difficult to understand when the final syllables of words arrive at slightly different times.

Large theatres were outdoor venues often built into the side of a hill. The apparent dryness of the resultant acoustic was also a problem for Vitruvius when dealing with music (although music was more commonly performed in smaller theatres which may have been roofed or offered other acoustic benefits) and he went to considerable effort to invent a system that would counteract it. Resonating bronze vases were his solution to this problem.

On many levels, the principle is desperately easy to disprove. No examples remain; even the niches (the housings where the vessels would be contained) are difficult to identify and there is disagreement about their positioning and function. Modern reconstructions appear to prove the concept as being ineffective. Why, then, would Vitruvius – the practical exponent of his craft and author of a series of books largely dedicated to practical problem-solving – dedicate so much space in Book I and Book V of *De Architectura* to *Êcheia*? Why would Vitruvius spend a disproportionately large amount of time examining the acoustic performance benefits of the theatre rather than its visual aesthetic? Whilst we may never fully know the answer to these questions, this chapter will examine the concept in detail in an attempt to unravel a fascinating enigma.

Vitruvius: the Person, Scientist, and Philosopher

Marcus Vitruvius Pollio studied Greek philosophy and science around the first century BCE. A practical exponent of his craft, he gained experience through his professional work and was the architect of at least one complete unit of buildings for Augustus in the reconstruction of Rome. As an indication of his diverse talents, he also oversaw developments in the imperial artillery and military engines. These various contributions made Vitruvius an important figure in his day.

In the modern era, Vitruvius has been regarded primarily as an architect, but his explorations of science and art in the widest sense should not be forgotten. The emphasis of books I-V is on architecture in the traditional sense of the word. The second of the five books contain information relating to Greek science that demonstrate the knowledge Vitruvius had acquired. The inspiration of science was at one with art and literature (although this was not a philosophy specific to Vitruvius).

Vitruvius had a liberal arts education that informed his professional training. Whilst it would be inaccurate to claim this training was common to all Roman architects, interdisciplinarity was at the heart of their learning. Music, or to be more accurate, the science of music and acoustics was a key aspect of Vitruvius' knowledge. As early as the opening chapter of Book I, Vitruvius states: "The architect should know music in order to have a grasp of canonical and mathematical relations…"[1]

Whilst proportion and knowledge of the science of acoustics is at the heart of much of Vitruvius' learning, it is important to remember he followed the teachings of Aristoxenus, who offered a philosophical alternative to the concepts of Pythagoras. This can be clearly seen in his approach to the study of music and vibration and how this relates to theatre design: "The science of the architect depends upon many disciplines and various apprenticeships which are carried out in the art."[2]

Details regarding music and theatres (and other public buildings) are to be found in Book V of *De Architectura.* Book I also makes reference to the principle of *Êcheia* and presents a detailed expose of the training of architects at that time. There is an emphasis here on the practical, detailing basic common sense and problem-solving.

Greek and Roman Music

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[1] Vitruvius, Bk I, Chap I (trans. Rowland).
[2] Vitruvius, Bk I, Chap I (trans. Rowland).

Vitruvius' *Êcheia* were based upon the musical principles of Aristoxenus, who lived around the fourth century BCE and wrote a number of works on music and related disciplines (his *Elements of Harmonics* survives). Aristoxenus can be considered the greatest musical theorist of his time and his work is recognised scientifically. Whilst the Pythagoreans formulated the modern science of acoustics in Greece in the sixth century BCE, Aristoxenus examined the study of musical sounds further by going beyond the source and propagation of sound to consider issues of perception. He became aware of how human life experienced sound, examining perception and other forms of sensory cognition. With this in mind, it is hardly surprising Vitruvius followed his work and applied it to the acoustics of Roman theatres.

Before exploring the reasoning behind Vitruvius' concept of the resonating vases in Roman theatres, it is important to have an understanding behind these principles. Whilst Vitruvius is at pains to state it 'is an obscure and difficult musical science,' the modern reader should find it more approachable:

> Harmony is an obscure and difficult musical science, but most difficult to those who are not acquainted with the Greek language; because it is necessary to use many Greek words to which there are none corresponding in Latin. I will therefore explain, to the best of my ability, the doctrine of Aristoxenus, and annex his diagram, and will so designate the place of each tone, that a person who studiously applies himself to the subject may very readily understand it.
>
> Vitruvius, Bk V Chap IV (trans. Morgan)

More is known about Greek musical theory than the music itself. Fragmentary examples include material 'notated' and written on papyrus in the Museum at Cairo and 'hymns' engraved in stone in the Athenian treasury in Delphi, both dating to ca. 250 BCE.[3]

The systems as described by Aristoxenus and Pythagoras are different in terms of both technical specification and philosophy. Aristoxenus sets out a theory of scale structure and a method for analysis. His definition of interval is different from that of the Pythagoreans (which is based on ratio and proportion) in that he describes two pitches as being bounded or marked off by two notes of different pitch. A system is a construction of intervals, the smallest group of which is known as a tetrachord.[4]

[3] Sachs 1943.
[4] Landels 2000; Belis 2001; Helmholtz 2009.

The *genera* (a scheme of three basic tetrachords) are concerned with intervals (that can be used to create melody). The starting point would have been standardized (A440 in modern terminology) but would have been based around a keynote (mesë). Aristoxenos and his followers did not subscribe to the doctrines of Pythagoras in terms of pitch ratio and objective forms of measuring frequency (an acoustic sound containing a musical pitch will normally contain many different frequencies within it). Rather, they used more subjective methods of controlling interval and described them as such. The three *genera* were used in melody to create a large number of sub-genera or 'shades' with intervals that were adjusted.[5]

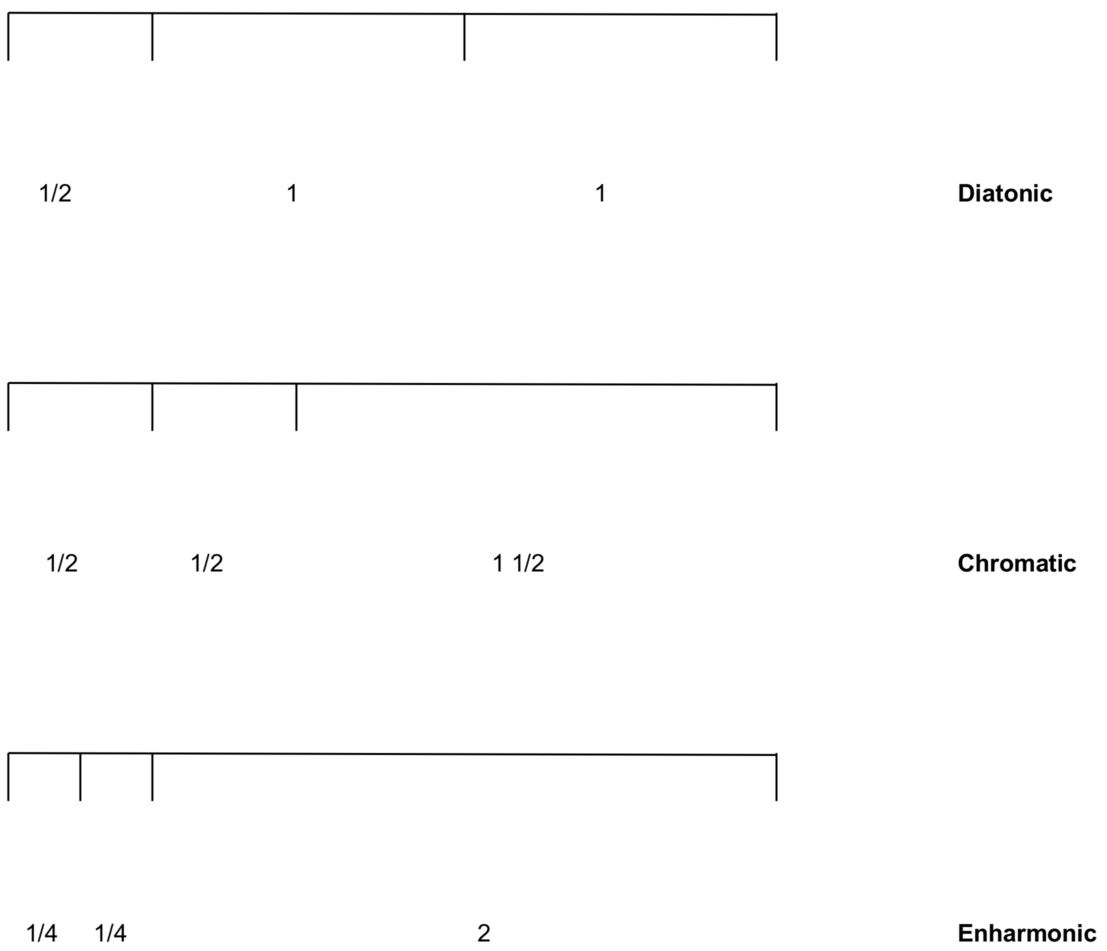

Figure 1 – the three *genera*

[5] Aristoxenus 1902; Sachs 1943; Landels 2000; Belis 2001.

The groups of four pitches in each tetrachord are always surrounded by the interval of a fourth. Aristoxenus demonstrates three different types (*diatonic*, *chromatic*, *enharmonic*). He uses the term *hemitonion* to describe an interval of a semitone and more complex term of *diesis* for any interval smaller than a semitone.[6]

He does use mathematical ratios to assist with the concept of microtones but also spoke of them in terms of colour and other descriptive methods. To make more complex pitch systems it is a simple matter of placing one tetrachord on top of another (giving tetrachords based on cycles of fourths). This developed into the Greater Complex System giving a two-octave construction. This is the method that Vitruvius follows for the tuned vases.[7]

Theatre Design

As is well known, the design of a Roman theatre has much in common with its Greek counterpart. The theatre of the Greeks was built on the slope of a hill, securing sufficient elevation for the back row from the naturally occurring landscape. The tiers were either cut directly into rock or, if the land was soft, an excavation was made in the hillside and lined with rows of benches. The steps were often faced with marble (as in the theatre of Dionysus at Athens). The theatre of the Romans was potentially a freestanding structure and therefore a much more complex design.

The size of a Greek or Roman theatre can vary enormously. They may seat many thousands of people (as with the Great Theatre in Amman, Jordan) to a few hundred (the theatre in Ostia). Vitruvius differentiated between large and small theatres when discussing *Êcheia* and reduced or increased the number of vessels accordingly.

[6] Binning Monro 2011.

[7] Landels 2000.

Figure 2 - the 6,000-seat, 2nd-century Great Roman theatre in Amman, Jordan together with the much smaller 500-seat theatre (Odeon) to the left

The difference in design and construction can be clearly seen, the smaller structure being a freestanding building and likely to have included a temporary wooden roof. The use and purpose of a large and small theatre would have been considerably different.

Vitruvius makes various statements about the positioning of theatres, often relating to practical considerations to do with heat on the audience or even drainage of land where the theatre is built upon. There are cosmetic differences between Greek and Roman theatres relating to proportion but it is also likely that these differences concerned practical problems connected with location. The *orchestra* is a full circle in a Hellenistic theatre and a semicircle in a Roman theatre. Of paramount importance was audience sight line of the *orchestra*, a common feature of all theatres. Having said this, there was still a hierarchy in place relating to the 'best seat' with different classes using different galleries. Proportions of the Vitruvian theatre were also based upon practical considerations. The length of the stage was twice the diameter of the *orchestra* in order to provide room for the large number of actors required in

Roman theatre. The stage buildings and *cavea* were united into one building, with the back wall of the stage reaching the same height as the back of the cavea.[8]

Figure 3 - The Roman Theatre at Aspendos, Turkey

The angle of raking varies in the seating of most theatres, although there are further commonalities in relation to entrances and other practical features.

The Acoustics of the Roman and Greek Theatres

Are the proportions of theatres decided upon for acoustic or aesthetic reasons, or is the acoustic an accidental benefit? All seats offer excellent sightlines, while the actors can be clearly heard, owing to the steepness of the raked seating providing an unrestricted view of the orchestra from any seat. Vitruvius praises the plan of the Greek theatre owing to its excellent acoustics and notes improvements made as a result of wood being used for the stage, doors, and (most notably) wooden roofs:[9]

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[8] Kenyon 1934; Bieber 1961; Sear 2006; Frederiksen 2015.
[9] Bieber 1961.

> The top of this magnificent stage building was covered by a wooden roof which was built out from the inner wall with a backwards slope. This roof was mainly to improve acoustics, not to shelter actors. The most important specialty of Aspendos theatre is its perfect acoustics, so that speech even in a normal voice in the orchestra can be easily heard from the upper gallery. This is the result of the way in which the stage-building was fully joined to the auditorium.
>
> Ozgur n.d.: 48.

While it is has been widely stated that Roman and Greek Theatres have 'excellent' acoustics in terms of spaces that provide great clarity for certain types of sound, most notably voice and speech, this is far from accidental. There are scientific reasons for why this should be.

Sound propagates from the source in all directions. When a sonic point source (speech for instance) radiates into free space (a space free from reflection) the intensity of the sound varies as $1/r^2$ where r is the distance from the source. An environment where there are no reflections is known as free field. The sound intensity level decreases by 6 dB each time the distance from the source is doubled. Free-field conditions rarely occur indoors as sound will only travel a short distance until it meets a reflecting surface.

Reflection of sound, usually with significant absorption, is at the heart of the science of acoustics. A flat surface will reflect the sound like a mirror; convex surfaces are likely to scatter a sound and concave surfaces will provide surface concentration of sound at certain points. A Roman or Greek theatre is an example of a concave structure. In order for clarity to be achieved in a theatre, reflections need to be directed away from the audience (although it should be remembered that the audience is at the reflective, not the focal, point).

Sound propagation in a room consists of direct sound (which travels from the source to the listener without reflection or interference of any type), first reflection(s) and then further diffuse reflections, which form the reverberation. In reality, an 'excellent acoustic' is one that is suitable for the purpose the building is intended. It is unlikely that an environment will be fully free-field (and nor would we consider this acoustic to be 'good' in most circumstances) and a balance is required between reflected sound and direct.[10]

Lasos of Hermione (c. 500 BCE) is credited with discovering vibration as a cause of sound. One hundred years later, Archytas of Tarentum claimed that these vibrations could be

[10] Rossing, Moore, and Wheeler 2002.

described as being of two types: ‘stationary’ waves in a musical instrument (a resonating box of some kind) and waves that moved in air to deliver them to the listener. Whilst modern scienctists might argue with these notions, there is an understanding starting to develop regarding the propagation of waves and sound in particular.

A greater understanding of acoustics can be identified in the structures of theatres (e.g., Dionysus at Athens and the theatre at Syracuse) as early as the beginning of the fifth century BCE. Whilst we may disagree regarding the acoustic intent, it is largely agreed that the shape of theatres was not based on scientific understanding but rather by accident. A site on the side of a hill, sloping down at approximately 45 degrees, gave a good acoustic result. Other portable solutions also helped the acoustic. Backdrops helped high-frequency reflections (provided by painted skins). It is believed the propagation of sound to the audience was aided by the megaphone effect of the masks worn by the actors. A Roman mask was a large full-face affair, portraying grotesquely exaggerated expressions that could be seen from anywhere in the theatre. But they were shaped in such a way that the spoken or sung voice may be ‘amplified.’[11]

In a Greek or Roman theatre, there are few physical objects that will create such interference. In an enclosed space, there are many. However, such interference is not seen as problematic in certain types of building, particularly if it is designed for the ‘performance’ of material suited to a diffuse reverberation. As can be seen from above, Vitruvius was aware that ‘echoes’ (as opposed to reverberation) were problematic for the spoken voice.[12]

Vitruvius discusses the acoustic characteristic of the theatre with particular regard to voice. He declares there are a number of places that naturally impede (dissonant), disperse (dispersive), or reinforce (consonant) the voice:

> *Katechountes*: dissonant sites. ‘Are those in which the voice, when first it rises upwards, meets solid bodies above. It is driven back, and settling down, overwhelms the following utterance as it rises.’
>
> Vitruvius, Bk V Chap VIII (trans. Rowland)

[11] Beacham 1991; Ley 1991; Sear 2006.
[12] Howard and Angus 2017.

Periechountes: sites that disperse sound. 'The circumsonant are those in which the voice moves round, is collected and dissipated in the centre. The terminations of the words are lost and the voice is swallowed up in a confused utterance.'

Vitruvius, Bk V Chap VIII (trans. Rowland)

synechountes: consonant space. 'The resonant are those in which the words, striking against a solid body, give rise to echoes and make the termination of the words double to the ear. The consonant also are those in which the voice reinforced from the ground rises with greater fullness, and reaches the ear with clear and eloquent accents.'

Vitruvius, Bk V Chap VIII (trans. Rowland)

Practically, there are acoustic problems with *katechountes, periechountes*, and *synechountes* in terms of clarity and intelligibility of spoken voice.

The plan views of Roman and Greek theatres have remarkable resemblance to the wave analogy of sound propagation.

Figure 4 – Faraday Wave experiment

Figure 4 shows the initial impulse pattern of a Faraday Waves experiment, created in 2015 by the author in collaboration with Professor Stephen Morris at the University of Toronto. Also known as Faraday Instability, they form non-linear standing waves that appear on liquids enclosed by a vibrating vessel. Whilst the analogy of the Faraday Wave experiment to sound dispersion is somewhat flawed scientifically (owing to non-linearity within the Faraday Wave experiment), the resemblance to the layout of a theatre is striking, as in the 'pebble in a pond' analogy.

Figure 5 – Southern Theatre, Jerash, Jordan

Figure 6 – the Great Roman theatre in Amman, Jordan

Further developments in the shape of theatres are all thought to have been due to attempts at improving the acoustics. An increased length of the seating area (whilst maintaining overall proportion) brought more of the audience close to the stage and thus improved the acoustics, especially as less of the sound could escape at the sides of the orchestra. However, the direction in which the actors were facing became of greater importance, and the height of the stage building was increased and made of stone to provide more reflection from behind and improve the distribution of the sound.

The "Evaluation and Revival of the Acoustical heritage of ancient Theatres and Odea" (ERATO) project was a three-year research scheme financed by the European Commission (INCO–MED Program). The project aimed to investigate the acoustics of open-air theatres and compare to the smaller, possibly enclosed theatres known as Odeion. Computer models of spaces were made with measurements being taken from the best-preserved structures including the Aspendos theatre in Turkey and the South theatre in Jerash, Jordan.

Perhaps unsurprisingly, analysis found that the Roman open-air theatres had very high clarity of sound. However, they differed from the odeion in that their structures resulted in a reverberation time similar to a small concert hall but with reduced clarity. This is a result of the *Odeion* being an enclosed structure (with a roof and further reflective surfaces). Importantly, the differing acoustical properties reflect the original different purposes of the buildings, with the theatre intended mainly for plays (speech) and the Odeion mainly for song and music:

> The soundfield in the Aspendos theatre is characterized by a considerable long reverberation time and Early Decay Time, EDT, but compared with roofed theatres or concert halls, the sound strength, G, is low and the clarity of the sound, C, (and presumably the speech intelligibility) is high due to a low level of the reverberant field—obviously caused by the absence of a ceiling.[13]

Whilst the ERATO study is the most significant in its field, the issue of *Êcheia* receives little acknowledgement and is largely disregarded.

Further portable structures—such as staging, panels, and sets, and potentially roofs—were constructed from wood. Evidence can be found from paintings and frescoes of enclosed porches and other temporary structures. Such enclosed structures would provide 'sounding box' effects although it is far from clear if the intent was acoustical. Vitruvius is clear about his knowledge of and his preference (acoustically) for wooden stages in stating how the boarding assists the resonance within the theatre.[14]

Perhaps most importantly, the inclusion of the large front wall known as the *skene* reflected sound back to the audience (in a similar fashion to 16th century theatre design). Performers were trained in how to maximize their voices by using the structures in combination with masks and costumes.[15]

In summary: there are many variables that have a direct effect on the acoustic of a theatre. Probably the most significant is the resultant change in acoustic when the space is filled with an audience: the space changes from flat raked reflecting stone to diffused shapes clothed in soft less-reflective materials. Most theatres in use today have undergone extensive renovation or may have major parts of the structure missing. Vitruvius was at pains to state that the positioning of Roman theatres should take into account environmental conditions (sun position and wind). But a significant difference when comparing a modern theatre of the to its origins over two thousand years ago concerns ambient or environmental sound. Even a

[13] Gade et al. 2004.
[14] Beacham 1991; Howard and Angus 2017.
[15] Sear 2006; Blesser and Salter 2007.

bustling Roman city would have been virtually silent environmentally, allowing a listener to hear all manner of things that we now cannot. What role might the *Êcheia* have played in this?

Acoustic Problems, Vases, and Concepts

Greek and Vitruvian understanding of acoustics is impressive for its time, although occasionally easy to discredit with modern knowledge. Vitruvius was aware of an acoustical problem caused by the reflection of sound waves: namely, that interference to the original source is created by reflections making the original less clearly audible or defined, which he labelled *resonantia*. If any extraneous, powerful reflections come back to a listener at slightly different times, then speech would have become difficult to understand. As Vitruvius pointed out, an inflected language such as Latin is difficult to understand when the final syllables of words arrive at slightly different times. Were resonating bronze vases were his solution to this problem?

> ... let bronze vases be made, proportionate to the size of the theatre, and let them be so fashioned that, when touched, they may produce with one another the notes of the fourth, the fifth, and so on up to the double octave.
> ... the voice, uttered from the stage as from a centre, and spreading and striking against the cavities of the different vases, as it comes in contact with them, will be increased in clearness of sound, and will wake an harmonious note in unison with itself.
>
> Vitruvius, Bk V Chap V (trans. Morgan)

As noted above, these ideas concerning acoustics are largely based on the writings of Aristoxenus.[16]

It has been claimed that the combination of vases might be considered an early artificial reverberation unit (although this is clearly problematic scientifically), with specific frequencies enhanced and others excluded. It is likely that the function of the vases would have been to make some frequencies louder than others by allowing them to resonate when certain harmonics ‘strike’ them. For instance, when a singer performs a perfectly in-tune scale, a number of vases would ring creating a harmonic chord. An artificial reverberation,

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[16] Aristoxenus 1902.

RT60 time estimated as 0·2–0·5 seconds containing only those harmonics listed in the vases pitches would be produced in an open-air theatre that would otherwise have little.[17] Science and appropriate testing of this idea makes this hypothesis doubtful, largely due to the large amount of energy required to make a vessel resonate (ring) in such a way.

There may be another purpose for the vases other than those already mentioned. Some believe the acoustic jars helped singers and those relying on ear for maintaining pitch to keep to proper pitch. As indicated, the resonance of the vases would have given emphasis to important pitches leaving the others silent. If the artificial reverberation concept is difficult to accept, the assisted resonance idea is perhaps a little more attractive.

Whilst there are no known original vases in existence, a number of sites show evidence of spaces (niches) where the vases would have been positioned:

> 12 pairs of compartments corresponding to those described by Vitruvius have been found in the supporting wall of the uppermost row of seats of the Greek theatre at Aizani in Phrygia, eight in the podium of the Roman theatre at Nicopolis, and seven in the Greek theatre at Scythopolis in Syria. There are 20 niches in the upper part of the Greek theatre of Gerasa in Jordan; at Lerapetra and Gortyn in Crete the theatres have 13 niches each; and at Lyttos, also in Crete, there are three rows of 13 niches each.[18]

Functionality

Each vase was tuned by altering the shape and area of the cavity of the vessel. Multiple vessels were placed around the theatre.

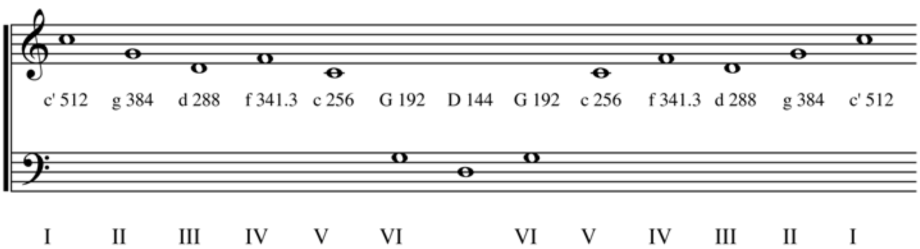


Figure 7 - vessel pitches for a small theatre

[17] Landels 2000.
[18] Lewcock and Pirn 2001: 81.

Vitruvius states that different numbers of vases should be used depending on the size of the theatre:

> The method of marking out the positions in which the jars are to be placed is as follows. If the theatre is not very large, a horizontal line should be marked out, halfway up the slope [of the auditorium], and 13 vaulted cubicles built, with 12 equal intervals between them: then the sounding jars as described above are placed in them.
>
> So by this arrangement, the voice, radiating from the stage as from a centre, spreads itself around [the auditorium]: and, by exciting resonance in particular vases, produces an increased clarity and a series of notes which harmonize with itself.
>
> Vitruvius, Bk V Chap V (trans. Rowland)

The fundamental frequencies listed here should be treated with suspicion. However, approximate vessel size and shape can be accurately calculated using the Helmholtz resonance formula:

I	nëtë hyper bolaiön
II	nëtë die zeugmenon
III	paramese
IV	nëtë synhemmenön
V	mesë
VI	hypatë meson
in media	hypatë hypatön

Figure 7 shows the pitches (with Greek names) of the vases for a small theatre as specified by Vitruvius. Vase I *(nëtë hyper bolaiön*) would be placed at either side of the theatre with the *in media* vase (D 144) placed centrally. All others would be equidistant between. Larger theatres required a greater number of vases arranged in three horizontal rows (for the *harmonia*, the *chromatic* and the *diatonic*).

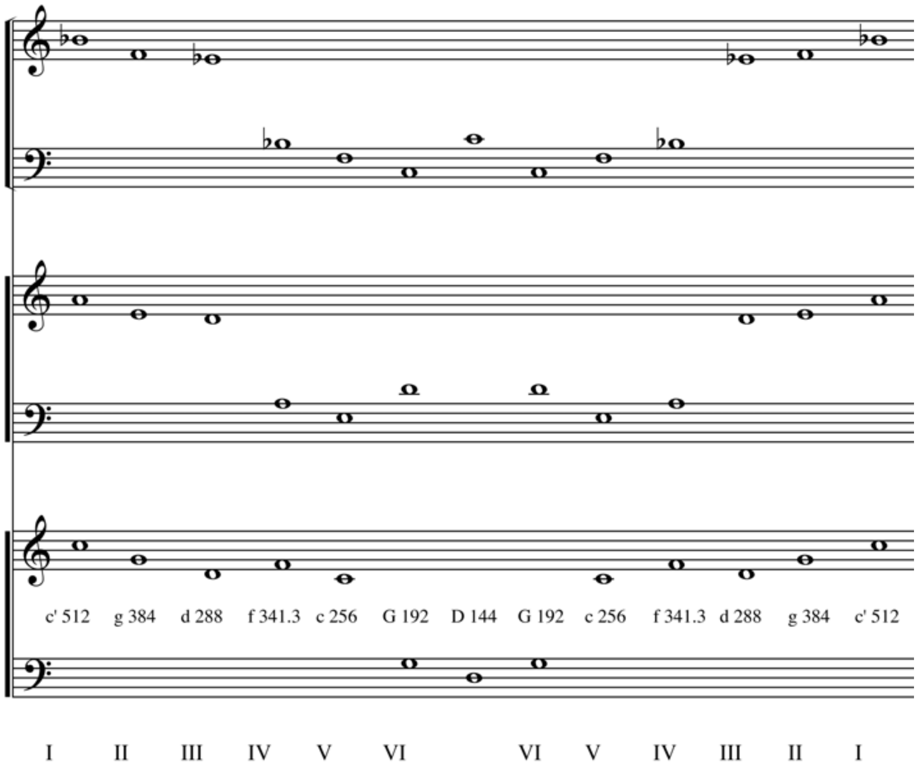


Figure 8 - vase pitches for a large theatre

Vitruvius discusses why acoustic vases were not used in the theatres of Rome. Owing to their wooden construction, singers who wished to increase the projection of their sound could direct their voices towards the scene doors (*valvae*). When a theatre is made of solid materials (such as stone), then it should be equipped with the vases as specified. Vitruvius states that there are many examples in Greek cities (Corinth). The expense of the bronze vases is also considered by Vitruvius: 'many clever architects who have built theatres in small cities, from the want of others have made use of earthen vases, yielding the proper tones, and have introduced them with considerable advantage.'[19]

It is wise to quickly remove other inaccurate preconceptions before really investigating the true intent and functionality of the *Êcheia*. As a freestanding structure, whether made from bronze or 'earthenware' (clay), it is the air within the vase that would cause the resonance. It is likely the actual material the vase is made from is largely unimportant; rather the volume of the interior of the vase is all-important when considering the intended frequency. Various translations of the Book V relate to the vases being struck.

[19] Bk V Chap V (trans. Morgan).

The layout and design of the vases clearly implies that 'struck' means sound enters the vase and the air is made to vibrate sympathetically. Vases are not struck in an analogous way to a clapper on a bell.

The closest scientific model of this practice relates to Helmholtz resonance. Helmholtz resonators (a type of resonant absorber) come in a variety of difference shapes and sizes and were originally used by H. von Helmholtz (1821–1894) to analyze musical sounds. An example of such a resonator is when you blow across an empty bottle causing the air in the bottle neck to vibrate.[20]

The all-important resonant frequency of the resonator is dependant on shape and area of the cavity, the cross-sectional area, and length of the neck.[21] Helmholtz resonators can have a variety of functions, but in architectural acoustics, they are used to *reduce* problematic low frequency content. This is done by analysing the problematic frequency (finding out its frequency value) and then building a resonator tuned to the problem frequency.

Any air cavity will provide a single resonant frequncy (not just a 'vessel' or Vitruvian *Êcheia*) when air is pushed into the volume and then released. Interestingly, the formula states, somewhat counter-intuitively, that a larger opening to the vessel will provide a higher frequency but a larger volume and longer neck will provide lower frequencies. Clearly, this area of science was unknown to Vitruvius. Was this phenomena discovered as a result of shouting loudly into a large oil container and hearing it ring? Different containers gave different frequencies with the volume being easy to change as result of changing the internal volume with more or less oil?

Vases of differing volumes created a fixed tuning system, based on the Aristoxenos system, not only enabling musicians to maintain tuning with others (i.e., an unaccompanied choir will often run the risk of falling flat without an instrumental reference point) but also maintain tuning for a solo voice. In the case of a theatre with the *Êcheia* system, a musician and particularly a singer could be 'tuned' to the building. Whilst this is at odds with the majority of research into this area, which focuses on the vases audibility, there is no doubt that the fixed tuning system is a benefit to the space (intentional or accidental…) as it is attenuating problematic frequencies, thus potentially improving intelligibility. However, if this were the vases only use, the placement as specified by Vitruvius would be different. It

[20] Rossing, Moore, and Wheeler 2002.
[21] Ginn 1978.

would make more sense for the vases to be closer to the performers, on or around the orchestra, and less focused on audibility for the audience.

We have only limited information as to how large and what shape they were (and this is important remembering the relevance of area of the cavity, the cross-sectional area, and length of the neck). This information varies depending on which translation you use of the Vitruvian text. As a result, a lot of reasoning and occasional down right guesswork is required in order to begin piecing together the enigma of function and intent.[22]

Positioning

Belli and Müller state there 'are 20 niches in the upper part of the Greek theatre of Gerasa in Jordan,' although their numbering is incorrect.[23] The North Theatre at Jerash has twelve niches, approximately 100cm x 80cm and 30cm deep, arranged in groups of three.

Figure 9 – the Northern Theatre, Jerash, Jordon

Figure 9 shows the niches referred to by Belli and Müller. However, niches can be found throughout Greek and Roman architecture in a variety of buildings, so we can only

[22] Pers. comm. Brüel and Godman, Pan-American/Iberian Meeting on Acoustics, Cancun, Mexico (2002).
[23] Lewcock and Pirn 2001:81.

guess if the intent of these niches was solely to house the *Êcheia*. Further translations of Book V state that the vessels are to be placed within the audience, possibly beneath the seats.

Figure 10 - The Roman Theatre at Aspendos, Turkey

The author is unclear as to the purpose and intent of this part of the Aspendos theatre in Turkey. There is no doubt that such an opening would function as a vented Helmholtz resonator (the rectangular hole is a neck to a chamber contained within). Might this, or similar, have housed a Vitruvian vessel?[24]

[24] Davis and Jones 1990.

Figure 11 [INSERT DIAGRAM FROM P246 VITRUVIUS CAMBRIDGE (5.5.1-8), currently wrong image]

Virtual Reconstructions: Impulse Response Method

By clapping your hands in a church, you are listening to the church's response to the impulse your palms have made (a short explosive sound), a means of understanding where we are in the acoustic world. Commercially available convolution reverb software is readily available. What this means is that it is possible to 'sample' an acoustic and use it as a plug-in of your choice. Audioease have developed *Altiverb*™, allowing the user the opportunity to combine a dry input sound with an impulse response created in a real acoustic environment. Their

Impulse Response Pre-Processor software allows the user to create his or her own impulse responses.

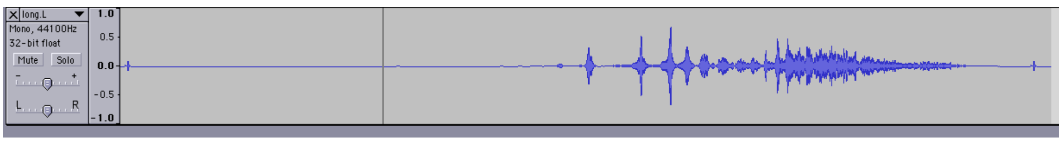
By clapping your hands (physically, or virtually with *Altiverb*™) near a Vitruvian vessel, you are listening to the vases response to the impulse made. Perhaps this is getting closer to an accurate digital reconstruction and a means of expanding into greater authenticity?

Physical Reconstructions

Early in his career, Per Brüel attempted to duplicate the resonating vase concept by physically building a series of vases to experiment with. None of Vitruvius' original diagrams illustrating the size and shape of the bronze vases survive so Brüel's experimental vases were made of clay in a wine-beaker shape. Brüel claims his experiments showed that they enhanced reverberation at the resonant frequency (although the vases were not tested in a real theatre).[25]

A vase closely matching the patterns detailed by Brüel, archaeologists, and historians was found recently in a farm shop close to the author's home. A Greek farmer was importing a variety of vases from Crete and selling them as garden ornaments, water-features, etc. By spending some time creating impulses and singing into the vases, it became clear to the author that these objects resonated quite effectively at certain frequencies and that these frequencies could be changed by placing material (sand, etc.) to change the volume within the vase.

A study of the vase was carried out in an anechoic chamber, which provided evidence of the vases effectiveness. A variety of impulse responses were created using the *Altiverb* ™ Impulse Response Pre-Processor software. Sinusoidal sweeps gave the best results when a good quality loudspeaker was placed around 150cm from the neck of the vase. The microphone used to record the sweep was also placed in a variety of positions, the most dramatic result being produced when placed several centimeters inside the neck of the vase.



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25 Pers. comm. Brüel and Godman, Pan-American/Iberian Meeting on Acoustics, Cancun, Mexico (2002).

(Hz)

683	3913
1070	4539
1407	4956
1790	5035
2150	5627
2465	
2759	
3130	
3211	
3518	

Figure 12 – waveform and numerical analysis

It is likely that there will be many higher harmonics, but those shown gave an accurate rendition of the resonance of this vase. Interestingly, it is far from obvious what the fundamental of the vase is. The impulse responses within *Altiverb* ™ gave interesting results when different sounds were played through them. Speech gave strong resonant results (particularly a male voice), which is probably to do with the resonant frequency of the vase coinciding with that of the voice, as is the idea. The frequency of the vase changed when the volume inside the vase changed.

Within the confines of an anechoic chamber, it is clear the vases and hence the *Êcheia* will have some effect. The vase rang audibly at a fixed resonant frequency when excited by another sound being present nearby. It rang more noticeably when a melody was sung which contained pitches held within the harmonic series of the resonant frequency, and less so when the melody deviated. With speech, it rang most of the time (male voice). This is because human speech contains a huge number of different frequencies sounding simultaneously. But even within an anechoic chamber, the effect is subtle. A large amount of energy would be required for a truly audible effect in a Greek or Roman theatre.

Synthesis

The impulse response method developed by Audioease through *Altiverb*™ is, by far, the best method of study, allowing for analysis and resynthesis. However, the author began designing software based upon the concepts of Vitruvius as early as 1999 using other synthesis methods using Max/MSP. The experiments began by building an additive synthesizer (a method that creates complex sounds by adding largely sinusoidal waves together) using the ratios specified by Vitruvius to explore the types of sound to be generated. Many assumptions were made as to how the vases would have sounded, with a principle assumption being that the harmonics would be largely sinusoidal. No attempt was made at modeling the amplitude envelope of the vessel, although it would have been relatively simple to do. This proved to be a very enlightening way to proceed as it made the author address issues of authenticity in the modeling process. Clearly this was an artistic reconstruction based upon the Vitruvian principle where many of the physical constraints (decay time and other naturally occurring acoustic phenomena) could be largely ignored as a result of being in the digital domain. Experiments were carried out using ten, sixteen and thirty-eight oscillators. These numbers were based up the number of vases found in theatres depending on their size. In the early experiments, one oscillator was used to represent one vessel. Clearly, a great many more oscillators would be needed using the additive method if an accurate representation was to be made, such is the nature of additive synthesis. Ironically, what began as a simple experiment produced some fascinating musical results. A combination of all available methods (physical and digital) may provide a truer picture that is realizable commercially, scientifically and artistically.

The Vitruvian Legacy

Other vases have been found throughout history and some are still in use. There is no doubt that Vitruvius' writings were the source for vases used in medieval churches. In Europe there are examples found in St. Clements, Sandwich, Kent; St. Peter Mancroft, Norwich; Fountains Abbey, York (all in the UK), and at St. Martin, Angers, Bjeresjoe in Sweden. Most of these jars are between 20 cm and 30 cm in length with fundamental frequencies of between 90 to 350 Hz (not far away from the pitches specified by Vitruvius). However, these examples of vases used in churches are likely to have been used to reduce reverberation and echoes by 'absorbing' resonance. Many were cemented into place and not placed loose as with the Vitruvian examples. So, with these many contradictions, it is hardly surprising that archaeologists are wary of the function of the vases.[26]

The Royal Festival Hall, London suffered from inappropriate acoustics since it was built. An electronic assisted resonance method was used in the 1960's, although the enhancement was removed in 1998. We now hear the natural acoustic (after further

[26] Harrison 1967.

alterations were made from 2005-2007 to raise the reverberation time), although the effectiveness of both natural and electronic enhancement remains deeply controversial.

Helmholtz resonators are widely used in room and studio design. Helmholtz bass traps can absorb low-mid and bass frequencies. Different types of absorbers can be used for dealing with many acoustic problems, from flutter echo, controlling reverb and stereo imaging in a room to standing waves and room modes. There is some similarity between the *Êcheia* and this concept.[27]

Artistically, sound artists and authors appear to have been fascinated by the notion. Thomas Love Peacock devotes a chapter in *Gryll Grange* (1861) to the premise, although he appears to find it unworkable in the end:

> This being done, the party assembled, some as audience, some as performers, to judge of the effect. The first burst of choral music produced a resonance, like the sound produced by sea-shells when placed against the ear, only many times multiplied, and growing like the sound of a gong: it was the exaggerated concentration of the symphony of a lime-grove full of cockchaffers, on a fine evening in the early summer.[28]

Halo for Piano and Responsive Electronics is a live musical composition by the author.[29] *Halo* uses the additive synthesis method to emulate the Vitruvian resonances and assisted resonance. But rather than being triggered by a sonic impulse, resonances were triggered by a responsive system detecting transient percussive attacks using Miller Puckette's Max/MSP *bonk~* external. As we are in the digital domain, we are not dependent upon further acoustic physical constraints. The quasi-assisted resonance approach has featured in most of the author's concert-hall and installation work ever since.

Conclusions

In the modern era, it is easy to imagine that everyone has a shared view that sound consists of pressure waves vibrating in air. Whilst the Greeks (and Vitruvius) had a good understanding of acoustics, before this period other 'reasons' may have been given for reverberation and 'echoes' that arguably contradict this potentially cold scientific view of what sound actually

[27] Jones 1990; Howard 2017.
[28] Peacock 1861, 133.
[29] *Halo* was recorded by Philip Mead and the author for the UH Record Label.

is. In Greek mythology, sound is represented by the figure of Echo, a former nymph. Upon being rejected by Narcissus, Echo physically crumbles, leaving nothing but her voice. But this voice could only repeat what was said to Echo..., a short time later (as an echo).[30]

Whilst our modern-day reading of the functionality of the *Êcheia* provides much disagreement and contradiction, there are a number of factors that are worth bearing in mind.[31] Ambient sound in Greek and Roman times would clearly have been significantly less than modern day. The loudest 'musical' sounds might come from a bell; or perhaps a Roman Bucina, a curved trumpet in the form of a letter 'G', some 3m long (as seen on Trajan's Column). Anecdotal evidence describes its sound as *"*harsh, raucous and terrible." But these sounds would have been relatively short-lived, working as an impulse. The subtle effects achieved by the *Êcheia* are more likely to be heard in very quiet conditions, the type of conditions you would expect in a Roman theatre when speech or song is the most important factor. We know from experimentation that the air inside a vase will resonate given the right conditions. Vitruvius states the vessels were only used in theatres built of stone as the wooden surrounds of smaller theatres would have provided a similar effect. It is less likely to form an artificial reverberation although a vase will 'ring.' It will function as a Helmholtz resonator, potentially aiding clarity of sound by reducing problematic and specific frequencies.

[30] Guerber 1907; Devereux 2001; Eneix 2016.
[31] Cox 2015.

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