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Acoustic Pots in Ancient and Medieval Buildings: Literary Analysis of Ancient Texts and Comparison with Recent Observations in French Churches

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Summary

During the last decade, acoustic pots inserted into the walls and roofs of medieval and modern churches have been the focus of renewed scientific curiosity after a long time of relative silence. Traditionally, authors from the Middle Ages to the present time considered that Vitruvius established the relation between the "vasa aerea" (bronze vessels) in ancient Greek theatres and the "fictilibus doliis" (earthen vessels). Vitruvius's text and philosophy is analysed with regards to acoustics, and his recommendations are compared with medieval, modern and contemporary texts about acoustic pots. Most of them hints at an acoustical purpose for the pots. Therefore, the literature survey is supplemented with an acoustical survey of 25 French churches where pots still remain. Recent measurements and observations in some those churches, completed with recent data from foreign studies, are consistent with an acoustical purpose of the pots to decrease the reverberation time at frequencies strongly excited by the spoken voice.

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1. Introduction

From the 10th to 16th centuries and even later, the practice of using acoustical pots as a common feature in church architecture spread throughout Europe. The question of their origin quickly emerged as a crucial one when we started research on the subject. Questions about the source and the development of this architectural device are recurring in the literature of the 19th century, the time at which the pots were discovered in the walls and the vaults of medieval churches. Even though the rare texts assign them acoustical purposes (see section 3), no account of the origin of the device and its heritage appears in sources contemporary to the installation of the pots, and the architecture textbooks of the late Middle Ages are silent on the matter.

In the 17th century, Mersenne [1] and Kircher [2] referred to available texts, such as Vitruvius [3], which contain a considerable amount of information on architecture and a much smaller component about the acoustical experience of his time. Consequently, the scholars connected pots with an ancient acoustic device, namely *echea*, a kind of bronze vessel, that Vitruvius describes within his description of Greek theatres (V, 5).

In the 19th century, these early works on Vitruvius's *De Architectura* were the only evidence of a possible acoustical origin and basis for the pots discovered in the churches. Researchers, archaeologists as well as acoustic specialists, accepted this evidence with little thought, comprehension or critical assessment. For more than one and a half centuries (1830–1990), the question of acoustic pots was mainly addressed by archaeologists. To our knowledge, the only acoustical studies have been by R. Floriot [4] in France, followed by J.-M. Fontaine [5] fifteen years later, abroad P. V. Brüel in Denmark in 1947 [6] and I. Koumanoudis, in Greece, in 1967 [7]. In the last two decades, the subject has seen a renewal of interest especially in Europe [8, 9, 10, 11, 12, 13], where a multidisciplinary approach has been employed [14, 15]. A large part of these recent studies has been recently published in French in a special issue of the "*Bulletin Monumental*"

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[16]. However, despite all these efforts, acoustic pots still raises numerous questions regarding the acoustical intention of those who inserted them in the buildings, sometimes a few centuries after completion [16].

The purpose of this paper is to present the state of the art, based mostly on French examples, of the studies on acoustic pots inserted in walls and vaults of edifices both in medieval and modern times, excluding pots inserted underneath the floor since they are not open to the interior space of the church [16]. A majority of authors consider that this research is difficult because of its multidisciplinary character. In France, a multidisciplinary team worked for almost 8 years on the subject, and its work has been published [16]. We recount here the results of this work, with more weight on the acoustical survey; however, to justify the research, we include a short analysis of Vitruvius's text, a census of the presently documented pots in France and Europe, and a non-exhaustive list of recent acoustic studies in Europe with their principal results.

Section 2 of the paper analyzes how the relation of pots to Vitruvius's vessels was perceived at the time of the discovery of the medieval pots, particularly in France. The acoustical experience of Vitruvius is reviewed, and his descriptions are analyzed in terms of acoustics and in relation to the pots inserted in the walls of the European churches.

In section 3, the studies known to date concerning the acoustic pots are presented in order to provide a progress report on the results obtained so far. First, the progress of the census of acoustic pots, in France and Europe, is presented. Then, we review, from French speaking countries, the available texts dating from the installation of the pots. Lastly, commentary is made on the known acoustic studies as well as on the principal results obtained by the authors.

Section 4 concerns a statistical study of around twenty-five French constructions made in order to check whether the data are compatible with an acoustical intention from the builders or those who inserted the pots. Data such as geometrical dimensions of the church, date of foundation, number and location of the pots, and resonance frequency of each pot, were collected. They show that the pots were probably chosen with respect to the human voice but also, and more surprisingly, with respect to the characteristics of the church since correlation is observed between the mean resonance frequency of the pots and the size of the church. However, as is well known, correlation does not prove causation.

2. Historical origins: Vitruvius and his commentators

2.1. History of the discovery in France

The writings of the 19th century (in France), devoted to the study of acoustic pots, show the genesis of the comparison, at that time, between the ancient bronze vases and the medieval acoustic pots. Among the articles, Didron [17], in 1862, makes the connection with the device which was placed in the church of the convent of Célestins in Metz, as recorded in its chronicle [18]. He supposes that the use of acoustic pots was abandoned in the medieval churches because of their insufficient effect on the acoustics of the churches, as the author of the chronicle claims it. The same year, Cochet [19] published an article on the acoustic pots and refers to Vitruvius (see also in English [20, 21]). In 1886, Vachez [22], raises the question in connection with the first acoustic pots discovered in France in 1842, in the medieval church of Saint-Blaise of Arles. On their subject, he declares that "the use of the *echea* is quite old", before expounding on the use of the earthen or bronze vessels placed in the Greek theatres intended "to reinforce the voice of the actors, but still to give more softness and harmony to the sound of music". Despite the scepticism of the contemporary archaeologists, the author endeavours to show that the *echea* were present in the Greek theatres. An affiliation between the ancient *echea* described by Vitruvius and the medieval acoustic pots is not in doubt for Vachez, who declares that "the transition was very natural, and we should not be surprised that they were introduced into our countries with Byzantine architecture. Moreover, recent discoveries in a great number of Russian churches lend credence to this view of their origin".

In 1902, when Enlart published his handbook of French archaeology [23], he quite naturally presents the medieval acoustic pots as a technical reapplication of the ancient model of the *echea* described by Vitruvius.

In connection with the pots found in the walls of the Saint-Victor church of Marseilles, Drocourt [24], in 1971, speaks about "resonators" and takes up the idea of Vachez, according to which "the Middle Ages perhaps adopted vases according to traditions coming from Antiquity or Byzantium".

So we see that the connection between Greek *echea* and acoustic pots made in the 19th and 20th centuries is more of an assumed connection without any supporting proof.

2.2. Vitruvius's knowledge of theatre acoustics

Vitruvius understood that sound propagates by setting air in movement. Vitruvius compares this setting of the air in movement with the setting of water in movement by a stone: "It is propelled by an infinite number of circles similar to those generated in standing water when a stone is cast therein, which, increasing as they recede from the centre, extend to a great distance, if the narrowness of the place or some obstruction do not prevent their spreading to the extremity; for when impeded by obstructions, the first recoil affects all that follow (V,3,6). In the same manner the voice spreads in a circular direction. But, whereas the circles in water only spread horizontally, the voice, on the contrary, extends vertically as well as horizontally. Wherefore, as is the case with the motion of water, so with the voice, if no obstacles disturb the first undulation, not only the second and following one, but all of them will, without reverberation, reach the ears of those at bottom and those at top (V,3,7)" [25]. The analogy was not well understood in classical times, and the passage was interpreted as sounds "go up stepwise". This misconception is long lived, because the belief that sound travels upward is still common today.

He understood the barrier effect, by which an obstacle, such as a spectator sitting in front, attenuates the sounds behind. Thus Vitruvius advises to align all the steps of the theatre: "whatever its effect might be on the stage (scena), to make it fall on the ears of the audience in a clear and agreeable manner." (V,3,8) [25]

Very probably, the observation of the barrier effect is at the origin of the belief that sounds curve upwards. Indeed, the spectators assembled on a horizontal plane, as was the case on the agora, the Greek meeting place, mask each other, so that one hears badly at the back. Whereas spectators assembled on a tilted plane do not mask each other any more, as was the case in ancient theatres. Thus, starting from a correct technical observation and despite correct analysis of the phenomenon – the significance of obstacles - an erroneous theoretical concept was deduced from it: sounds go up.

He classified the acoustics of places according to a classification that is still valid today. Thus, he distinguished between deaf places; "circonsonant" places where sound 'turns round' - in today's words: reverberating; "resonant" places, where a frank echo is heard; and "consonant" places which amplify sounds (V, 8, 2). Once again, despite a sharp ear enabling him to hear the phenomena correctly, he adds explanations that are often right, but at other times his explanations are completely erroneous and even in contradiction with preceding observations. Thus Vitruvius reckons that, in deaf places ("dissonant"), "The dissonant places are those in which the voice, rising first upwards, is obstructed by some hard bodies above, and, in its return downwards, checks the ascent of its following sounds." (V,8,1) [25]. Whereas some pages earlier, in connection with the curia, the building where local government held office at the time of Vitruvius, the same effect is analyzed differently: "The walls, moreover, at half their height, are to have cornices run round them of wood or plaster. For if such be not provided, the voices of the disputants, meeting with no check in their ascent, will not be intelligible to the audience. But when the walls are encircled round with cornices, the voice, being thereby impeded, will reach the ear before its ascent and dissipation in the air. " (V,2,2) [25]. The same effect, "obstructing the ascendance of sound by a solid obstacle", thus gives different results according to Vitruvius. Today we know that the last analysis is the correct one, however not due to 'obstruction' but to reflection of sound downward.

2.3. Acoustic analyses of Vitruvius's text on sounding vessels (V.5)

In the 16th century, Mersenne and Kircher and more recently R. Floriot [4] and P. Liénard [26], agree that Vitruvius's text raises many questions. Without discussing the principle of the relation between the two devices, all these authors see little resemblance in the basic principles of the ancient *echea* and the pots inserted in medieval and modern churches.

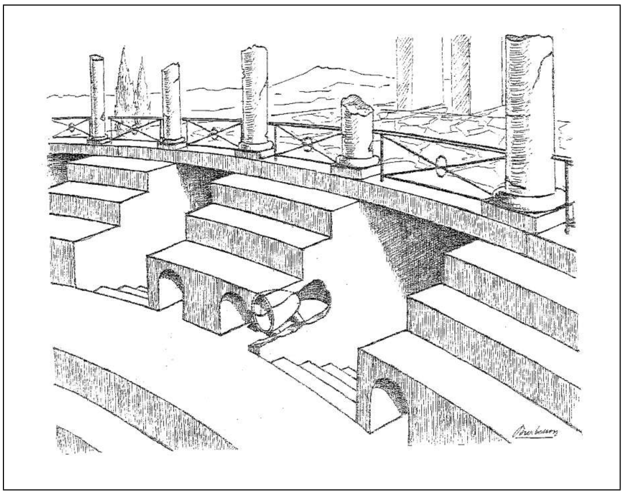

Figure 1. R. Floriot's reconstruction of Vitruvius's *echea* (after Panckoucke's 1847 publication of Vitruvius).

According to Saliou [27], Vitruvius idealized the ancient Greek civilization, and "The ten books of Architecture" is a work to the glory of its architecture. Vitruvius had the ambition to influence Roman contemporaries, with the objective of assimilating the Greek architectural techniques considered as superior.

Vitruvius's text falls into three parts. The first is descriptive and presents the ancient device which consists of cavities, which were located at various places within the Greek theatres and were spacious enough to include "vessels". A reconstruction is shown in Figure 1 (by R. Floriot). The second part gives an interpretation of the functioning of the device with a musical approach, according to the Roman-Greek culture. Lastly, Vitruvius provides evidence of the ancient Greek technique at his own time.

2.3.1. Physical description

If we take the description of Vitruvius according to R. Floriot, these vases would be, in fact, kinds of metal "bells" since Vitruvius speaks of striking them: they "are formed so as when struck, to give sounds, whose intervals are a fourth, fifth, and so on consecutively to a fifteenth" [25]. These "bells" are located in niches laid out between the steps of the theatres with a long neck of two feet (60 cm) and a height of half a foot (15 cm). The "bell" is inserted in the cavity and is supported by wedges of half a foot, which is the same height as the neck. The niche must thus be higher, about two or three feet (60–90 cm) what makes the internal volume larger than the volume of the neck. It is interesting to notice that only the niches are similar to the medieval resonator (with a much lower resonance frequency!) but not the "bell" which seems to be a vibroacoustic resonator.

Mersenne mentions already that "it is difficult [to believe] that they [the vessels] would be powerful enough to make their *consonances* heard by the listeners, when they are struck only by voices" [1]. Thus right from the start of the acoustic studies, the effectiveness of the device described by Vitruvius is already doubtful. Authors represent it like a vibratory system excited by the voice. Actually, Liénard notices that the system described by Vitruvius is the coupling of two resonators in cascade: the niche and the bell.

2.3.2. Functioning

The physical explanation of "vasa aerea" given by Vitruvius is related to musical harmony, as developed by Aristoxenus [28] because he states that "...the voice which issues from the scene, expanding as from a centre, and striking against the cavity of each vase, will sound with increased clearness and harmony..." (V,5,3). Aristoxenus considers that musical harmony must be dependent on the ear, and not only on mathematics as considered by Pythagoras and his disciples.

However, the bronze vessels would be expected to have sharp resonances, that is, displaying narrow bandwidths, as usual for metallic structures. Supposing that they could be excited by the voice, we can wonder what could be the value of such a device for the audience. It would have maintained a harmonic background but not created sound correction or local amplification. R. Floriot emphasises, that, for a nearby spectator, the device would "only generate annoying resonances".

The explanation provided by Vitruvius may also be interpreted as symbolism, as proposed by B. Poulle [29]. The author considers that the acoustic effect would come "only in second place in the intentions of the ancient architects" and he supposes there would be "behind the musical system of the acoustic vases, the theory according to which the theatres give an indication of the universe [...]". In this interpretation, the author suggests that the ancient acoustic vases would be, above all, a whole celestial representation, where each *echea* represents a planet and its sphere which emits its own unique hum, based on its orbital revolution and imperceptible to the human ear. This theory is known as the "theory of spheres". Developed during Antiquity, it has exerted durable influence during the Medieval Times with the geocentric representation of the universe [30, 31, 32].

2.3.3. Relation with earthen vessels

In the final part, Vitruvius establishes the relationship between some practices of his time and those of the ancient Greek epoch. He remarks, first of all, that the theatres in Rome are built of wood and that wood "resounds". This is why, he says, actors spontaneously turn towards the doors which reflect and amplify their voice. The connection between wood panels and bronze vases is surprising. The acoustic properties of metal vases and wood slats are quite different. Considering modern acoustical knowledge, the logic of Vitruvius could be: if the theatres are built with stones (which do not "resound"), it is necessary to help the singers (actors, musicians) with some device.

To the modern acoustician, this assertion that stones do not "resound" is strange indeed, since stones produce strong clear reflections, just as wood. But in his *De Anima* [33], Aristotle explains why. First, he writes that "bronze and in general all things which are smooth and solid [...] are said to have a sound because they can make a sound". But "not all bodies can by impact on one another produce sound; impact on wool makes no sound, while the impact on bronze or any body which is smooth and hollow does. Bronze gives out a sound when struck because it is smooth; bodies which are hollow owing to reflection repeat the original impact over and over again" (V,8). Therefore, only sound impinging on a hollow body, such as wooden laths, can "resounds"; stones, which are not hollow, cannot "resound", but only reflect sound, since Aristotle writes further: "It is probable that in all generation of sound echo takes place, though it is frequently only indistinctly heard. What happens here must be analogous to what happens in the case of light; light is always reflected" (V,8). Notice also that Aristotle specifically refers to bronze, the materials that *echea* are made of.

The text ends with an open question: "*Multi autem sollertes architecti, qui in oppidis non magnis theatra constituerunt, propter inopiam fictilibus doliis ita sonantibus electis, hac ratiocinatione compositis perfecerunt utilissimos effectus*", which could be translated as "Many clever architects who have built theatres in small cities, have made use, from the want of other resources, of earthen vessels, yielding the proper tones, and have introduced them with considerable advantage" (V,5,8). Thus, we see that Vitruvius makes the connection between the *echea*, known since the 5th–4th century BC and the pots inserted in the walls at around 25 BC.

3. Census of pots, texts, and past studies

3.1. Census of pots

While pots may be found in the whole of Europe, the census published in [16] reveals interesting details about the distribution. Figure 2 presents this distribution in France, and Figure 3 in Europe, both with greater precision than in [16]. Currently, we do not know any study of how the technique propagated in Europe, although it is traditionally regarded as coming from the Near East together with Byzantine architecture (see section 2.1).

Whilst the study from which our conclusions are drawn cannot be regarded as exhaustive, we feel it fairly represents the overall picture. In France for example, it is difficult to know if one finds more pots in certain areas, because perhaps in these regions:

- The technique had more success.
- The wars were less destructive.
- The "restorations" were less intrusive.
- The installation of acoustic pots came at later times.

This last point seems to be the case in Brittany where churches with acoustic pots are generally 16th century [5].

An uneven pattern of distribution is observed in Figure 3 for Europe, but this may be misleading because reliable data collection is lacking from many countries.

Another bias in the data is that pots may be hidden or have been destroyed during restorations. This is clearly

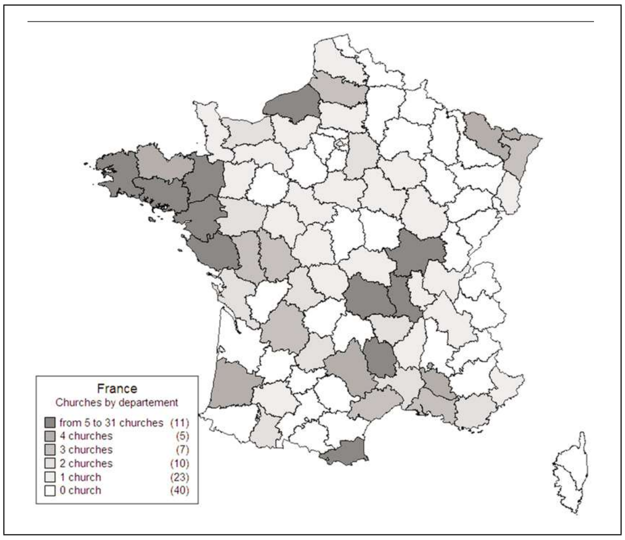

Figure 2. Distribution of acoustical pots in French churches – the map presents the French *départements* shaded according to the number of attested buildings with pots; for each shade, the number of corresponding *départements* is given in parentheses.

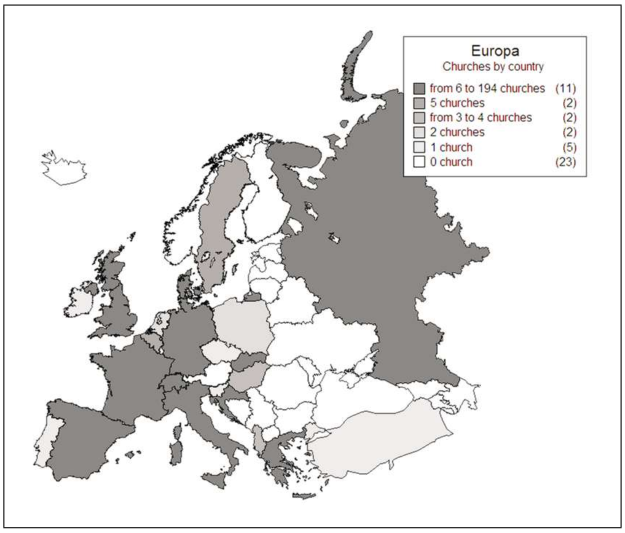

Figure 3. Distribution of acoustical pots in Europe – the map presents the countries shaded according to the number of attested buildings with pots; for each shade, the number of corresponding countries is given in parentheses.

the case in France. The studies of Floriot [4] in the 1950s and 1960s allowed the inventory of many not yet recorded buildings in the Rhône valley and in Provence. At the beginning of the twentieth century, local scholars, such as Cochet in Normandy [19], Baudoin in Vendee, Pays de la Loire and Poitou [34] or, later, Castel in Brittany [35] collected much data in their regions. Thus authorities and the general population were more aware and avoided destroying the pots at the time of restoration of their church.

Thus during our research on French regions, we "proselytized" in order to raise the consciousness of local authorities and state and regional archaeological services so that they preserved pots. An example comes from Brittany where copies will now replace missing or broken pots during a church restoration.

3.2. Historical texts

Analysis of texts written at the time of the vases shows acoustical intention from monks and church builders.

A chronicle of "Célestins de Metz" monastery in 1432 [18] states: "[il] *fit et ordonnoit de mettre les pots au cuer, portant qu'il avait vu altepart en aucune église et pensant qu'il y fesoit milleur chanter et que il ly resonneroit plus fort*"[1]

The book of minutes of the chapter in "Saint Denis de Vergy" in 1616 [36] records: "*Payé 24 sols au tupinier de Belon pour trois douzaines de petits pots pour mettre dans la muraille du chœur, propres à faire résonner la voix*"[2]. There are more than ten texts (at least in France) which explicitly mention a probable acoustic role for pots [37].

Few contemporary texts have been found but all of them attest to the acoustic purpose of the device.

The texts of the first acoustics experts like Kircher [2] in Germany or Mersenne [1] in France also contain interesting and relevant comments. For example, "*C'est pour cette raison que l'on met des pots à moineau, ou d'autres vases creux dans les voûtes, ou sur les voûtes des églises, afin d'aider les voix de ceux qui chantent...*"[3].

In medieval architecture textbooks, such as Alberti [38] or Philibert de l'Orme [39], where acoustics, under the name of "theory of music", essentially addresses the question of intelligibility by referring to Vitruvius and Aristotle (see sections 2.2 and 2.3.3), there is little or no mention of the pots. In 1743, the architect Salomon [40] had to rebuild a ruined church of the Dominican convent of Strasbourg. He comments about finding pots in the wall: "*En démolissant les murs du grand choeur du temple-Neuf (commencé en 1307, achevé en 1345), j'ai trouvé autour des ogives des fenêtres et noyés dans la maçonnerie des pots en terre cuite, l'orifice étant à fleur du mur vers l'intérieur. J'ai réussi à en sortir quelque uns intacts. Ces pots sont en terre grise.... Il y a longtemps qu'on a dû renoncer à croire à l'efficacité de ces pots pour l'acoustique, car tous les orifices étaient bouchés et le crépis les recouvraient complètement. Autour de chaque ogive se trouvaient neuf pots, l'un au sommet et quatre de chaque côté. [...] Apparemment que ces pots servoient à augmenter le ton des voix lorsque les Religieux chantoient au choeur*"[4].

[1] He ordered to put the pots in the choir, arguing he had seen elsewhere in other church and thinking that the song was better and stronger resonant.

[2] "Payed 24 sols at the potter of "Belon" for three dozens of small pots to be inserted in the wall of the choir, in order to better make resound the voice"

[3] "For this reason one puts sparrow pots or other hollow vases in the vaults, or on the vaults of the churches, in order to help the voices of those which sing..."

[4] "When demolishing the walls of the great choir of the temple-Neuf (begun in 1307, completed in 1345), I found earthen jars around the ogives of windows and buried in the masonry, the opening being flushed and open to the inside. I managed to extract intact some. These pots are in grey earth... Belief in the effectiveness of these pots for acoustics

3.3. Known acoustic studies

For a long time, this subject was only considered by archaeologists or by local scholars interested in artefacts found in their city or region. However, in the 1950s and 1960s, with the development of acoustics and especially of equipment for sound measurement and recording, these pots began to be scientifically studied: P.V. Bruel in Denmark (1947) [6], R. Floriot, in France, in 1964 [4], I. Koumanoudis, in Greece, in 1967, [7], J.-M. Fontaine in France in 1979 [5].

During the last ten years, various studies have been undertaken in Europe by archaeologists and acousticians: A. Kottmann in Germany [14], V. Desarnaulds *et al.* in Switzerland [8, 9, 41], M. Mijic and D. Sumarac-Pavlovic, in Serbia [10], A. Boato in Italy [11], T. Zakinthinos and D. Skarlatos in Greece [12], J. D. Polack [42] in Albania and a consortium of researchers in France coordinated by ourselves [16].

Figure 4. View of the vault in the nave of the church of Pommiers en Forez in Auvergne (France). Originally, each of the 29 holes corresponded to a pot. Only 27 are still in place, and 16 are unbroken. Bottom left: one of the pots removed from the roof and restored.

4. Statistical study of 25 French buildings: methodological approach

The ancient texts presented in the previous section leave little doubt about the acoustical intention of some of the church builders, or of those who inserted the pots. But they do not indicate the way in which pots modify the acoustics. Even the *in situ* experiments related in section 3.3 give no conclusive results. These experiments can be classed in 3 groups: in the first group, a noticeable amplification occurred [5]; in the second, nothing appeared clearly [5, 9]; and in the third one, a reduction of reverberation was slightly perceptible [8, 12]. These last experiments involved a large number of modern pots placed on the ground: Carvalho *et al.* [8] used 30 pots in a reverberant chamber; and T. Zakinthinos and D. Skarlatos [12] 300 pots in a church.

These studies showed that any acoustic effects of the pots (amplification, absorption,. . .) are difficult to prove. Therefore, the present study was limited to collecting, using a simple experimental method, all the data on the pots and their environment, likely to influence the acoustics. About fifty French church buildings with pots have been visited. Geometrical measurements of the church were made, details of the type and construction of walls were collected, and the pots were studied in order to measure their resonance frequency and to collect the related data (position, size of the neck, visualization with a web cam of the internal volume. . .). Only half of the buildings could be fully studied because of missing data for the others: for example, pots were out of reach, broken, or removed because of a recent restoration. The objective was to correlate the data related to pots in order to compare them with church geometry (volume, height), history, positioning, and use (monastic, parish). The results are then compared with present understanding of room acoustics, in order to determine if empirical knowledge could have been the basis of the choice of the pots.

This section first presents the selected churches and the methodology for the acoustic measurements. Then, the collected data on the pots is compared with church characteristics (volume of the church, height, use of the church, position in the church. . .). Finally, the resonance frequencies of 197 pots measured in eleven selected churches are analyzed according to the volume of the churches.

4.1. Selected churches and methodology

4.1.1. Churches

More than 320 churches have been listed in Europe and in the Near East as containing acoustic pots, from which there are approximately 200 in France [16].

Of fifty buildings visited in France (Poitou-Charentes, Brittany, Loire Country, Aquitaine and Auvergne (an example from Pommiers en Forez is shown in Figure 4), only the pots in 25 churches could be measured. The churches visited in the south, the middle and south-west of France date mainly from the period between the 11th and 13th centuries while those of Brittany, which are generally well preserved, belong rather to the 16th century. However, in some of the 12th century's churches, it appears that the pots were inserted in the 14th or 15th century during restorations. Thus we probably have an overrepresentation of late churches, owing to the fact that our study mostly includes Breton churches.

For some data, we included churches where the pots could only be counted, because their height made them inaccessible, and in some cases this included data collected by foreign colleagues [9, 14].

has been abandoned long ago, because all the holes were sealed and the roughcast covered them completely. Around each ogive were nine pots, one at the top and four on each side.(. . .) Apparently these pots were used to raise the tone of the voice when the religious sing in chorus."

Table I. Overview of the published experimental studies.

	Authors	Main results
Experiment *in situ* in real church	Fontaine (1979)	Amplification and decrease of reverberation time
Experiment *in situ* by reconstitution	Floriot (1964), Zakinthinos and Skarlatos (2006)	Decrease of reverberation time
Experiment in laboratory	Floriot (1964), Desarnaults (2002)	Decrease of reverberation time, transient regularisation, diminution of focalisation and stationary wave
Measurement of pots and estimation using room acoustic concepts	Kottman (Dreager consulting) (2008)	Decrease of reverberation time
Pot measurements	Floriot (1964), Valiere *et al.* (2006–2009), Polack (2011), Mijic (2004)	Choice of pots. Characterisation of pots.

4.1.2. Methodology

For each church, we tried to record:

- The number of visible pots *in situ*,
- An estimate of the total number of pots,
- Their positioning (nave, chorus, transept, several places) and how they were arranged (horizontal line, square, triangle, around bays, or atypical diagrams).
- The height at which they are positioned,
- The height of the church (walls, vaults…), its surface area,
- The type of ceiling (panelled frame, with boxes) or the type of vaults (stone or wood, in cradle, semicircular arch or broken),
- The type of walls (plastered or stone),
- The volume of the church, estimated from the height of the church and the shape of the vault.

Where we had access to the neck of the pots or when some of them had been extracted from the masonry, the length and the area of the neck were measured and the internal volume estimated.

For each pot, one or more recordings were carried out using a device made up of a carbon fibre pole 10 m high fitted with a KE4 Sennheiser electret microphone mounted on a tripod (Figure 5) and a web cam (628×582 pixels) remotely controlled.The position of microphone is about 1 cm from the entrance of the neck. Thus, it was possible for only one person standing on a bench or a small ladder to reach pots up to 12 meters high. The microphone was connected to a Dell laptop with its inbuilt sound board running a real-time analyzer (freeware Voce Vista RealTime, version 2.2, 2001) and spectral analysis, making it possible to check the measurements before storing them. Thus, broken pots can be sorted out, so that only measurements from intact ones are stored.

The responses of the pots to two types of excitation (repeated handclapping; and broadband noise) were recorded. Handclapping permits a quick estimation of the resonance frequency of the pots, and was used as a sort of "screening method" when reliable power supply was a problem. The aim was to propose a very simple procedure using standard equipment which could be used by archaeologists on a large scale.

Figure 5. View of the top part of the carbon fibre pole fitted with tripod and microphone – the microphone points to the opening of a pot.

4.1.3. Analysis results and protocol of selection of the data

Resonance frequencies of the pots *in situ* were estimated from the frequency responses and then compared with the frequency calculated from the geometrical data collected on the pots when those were accessible.

In the laboratory, the data was analyzed more precisely. For many measurements, the frequency response did not display the characteristic response of a pot (peak at Helmholtz frequency and at some non-harmonic partials). These pots did not function as Helmholtz resonators because they were cracked or filled with accumulated debris (dust, potsherds, bird droppings). These measurements were excluded from the statistics. The films captured with the webcam were also used to confirm if pots were broken or not. However, the surface state of the pots was sometimes difficult to observe even with the webcam, and the damping at resonance was not easily determined. With experience, the measurement of frequency responses was very reliable. Therefore, only the resonance frequency was collected.

A preliminary experiment was carried out to evaluate the uncertainties of a measurement *in situ*. The measurment microphone was positioned inside the pot, in the neck, at the exit of the neck, and finally at 10 cm outside the opening. Comparison was made with simulations based on the analytical equations of the radiation of a baffled Helmholtz resonator. The experiment showed that, by using a quarter inch microphone, the relative measurement error on the resonance frequency estimation does not exceed 3% (roughly one quartertone) as a result of differences in the position of the microphone (see Table II for mean resonance frequencies). In practice, the neck was sometimes accessible, but the volume was difficult to determine. Moreover, for pots which appear identical, the thickness of the surrounding plaster coating can lengthen the neck and thus modify the resonance frequency. Even though the error never exceeds 3% in laboratory conditions, many sources of error can arise in field conditions. Insertion conditions in the wall can be different for two identical potteries: the neck can be shorter or longer depending on the mortar; hand-made pots can be slightly different, etc.. . . Thus, we consider that two pots are similar if their resonance frequencies differ by less than 10% - roughly three quartertones.

Experience showed that, if the pot is cracked or if it contains debris inside (nest, straw, mortar, etc), the error is generally much higher than 10%. Thus, this value of 10%, slightly larger than three quartertones, was used either to distinguish two groups of pots or to sort out pots that are probably damaged.

Out of the 25 churches whose pots were measured, eleven had a sufficient number of non-broken pots to be included. Table II lists the estimated volume for each church, the number of pots in good conditions, and the average resonance frequency. The churches for which the spread in frequency exceeds 10% were initially isolated. Five churches appear to have only one type of pot, as the χ^2 test is rather high and near 1 (bold lines in Table II): a value of χ^2 equal to 1 indicates that the sample is Gaussian distributed, and large deviations from Gaussian distributions are measured by small χ^2. When two types of pots are assumed for the other churches, the spread in frequency reduces to less than 10% (not tabulated in Table II). One church remains undecided (Le Juch), the spread is small but the χ^2 is too small. It seems probable that there are two types of pots but rather close in frequency.

It should be realized that a standard deviation of 10% or less for the resonance frequencies of the pots is a remarkable achievement for those who inserted the pots, considering the acoustical knowledge of the time. Indeed, apparently identical pots can have different resonance frequencies, due to different actual neck lengths, as explained above. The difficulty is attested by Alberti in the 15th century, who writes about the tuning of the *echea* recommended by Vitruvius that “it is easy to say, but experts know how difficult it is in practice” [38].

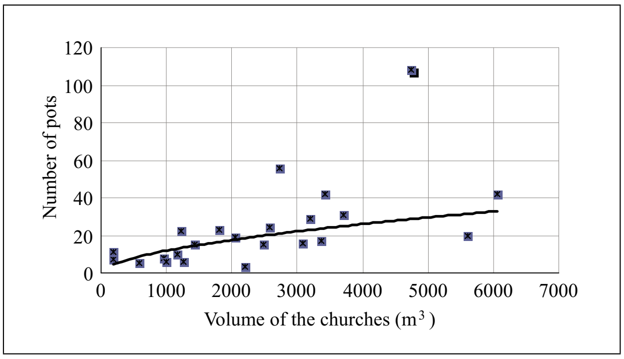

Figure 6. Number of pots in the 23 smallest French churches as a function of church volume.

4.2. Main results

The full analysis of the geometrical data has been published in reference [16] (in French). The principal results are listed below.

No trend is evident according to the nature of the church, or to monastic or parish use.

The mean number of pots (broken or not) by church (648 pots) is about 25, which is also the value found by Floriot in 1964. On the other hand, (Figure 6) the number N of pots increases with volume as

$$N = \alpha V^{0.55}, \qquad (1)$$

with $\alpha \approx 0.24$ and a correlation coefficient of $R \approx 0.61$. This result suggests that those who inserted the pots understood that the effects were cumulative, and had some empirical knowledge of acoustic rules.

Figure 6 was obtained with only 23 French churches with volumes smaller than 6000 m^3. To confirm the power law relation between the number of pots and the volume, we have added the measurements data from 2 other French churches with volumes larger than 6000 m^3 for which full measurements of the resonance frequencies have not been possible. We also added the data from 3 Swiss and 1 German churches [8, 14]. The same trend is found with a power of 0.6 for the volume ($\alpha \approx 0.15$) and a somewhat higher correlation of $R \approx 0.71$ (Figure 7).

Figure 8 displays the mean height at which the pots are installed for 23 out of the 25 churches, as a function of nave height - two churches could not be measured because the nave was too high. Pot height is proportional to the height of the building, with a correlation coefficient of 0.77.

Table II. List of selected churches with pots in good working order. f is the mean resonance frequency of the pots for each church (line in bold type) and f_1 and f_2 are the mean frequencies if the churches have two types of pots (line not bold). std is the standard deviation of the distribution, given in percent of the mean resonance frequency. The χ^2 test checks the validity of the sample in case of a church with only one type of pot, by comparing its empirical distribution to a Gaussian one.

Church	Volume (m^3)	Number	f (Hz) (std %)	χ^2	f_1 (Hz)	f_2 (Hz)	f_2/f_1	Type
Quinçay	**953**	**8**	**398 (5%)**	**0.73**				**One**
Le Trévoux	**1172**	**10**	**169 (6%)**	**0.85**				**One**
Trégourez	**1439**	**12**	**372 (10%)**	**0.97**				**One**
Ergué Armel	**2050**	**17**	**437 (10%)**	**0.82**				**One**
St Blaise (Arles)	2486	15	272 (22%)		220	331	1.50	Two
Quemeneven (Kergoat)	2736	22	135 (26%)		106	171	1.62	Two
Pommiers	3200	16	210 (14%)		196	246	1.26	Two
Le Juch	3419	37	126 (11%)	0.48	122	149	1.23	Unclear
Moisdon la rivière	3699	9	251 (18%)		212	283	1.34	Two
Ploaré	4739	45	171 (14%)		141	184	1.30	Two
Chemillé	**5615**	**6**	**124 (6%)**	**0.82**				**One**
Total		197	242		166	227	1.37	

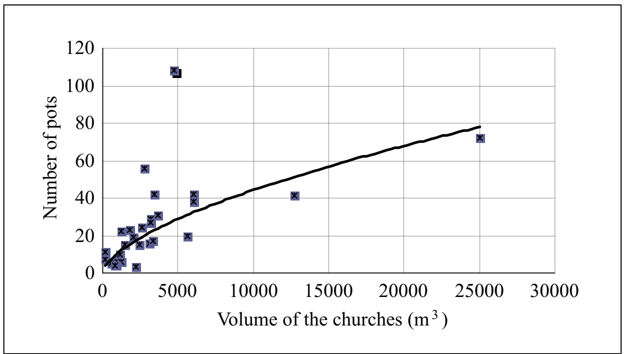

Figure 7. Number of pots as a function of church volume. Data includes all measured French churches, 3 churches from Switzerland [8], and 1 church from Germany [14].

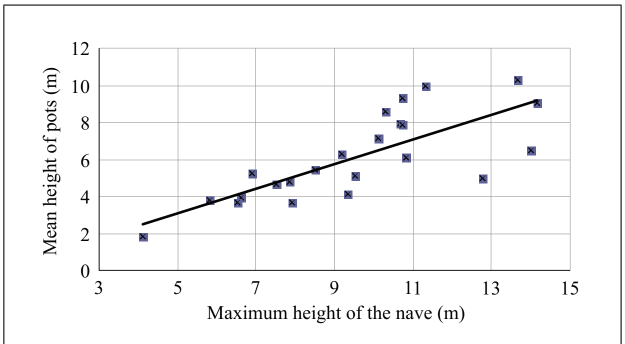

Figure 8. Mean height of pots in 23 French churches (see text for selection criterion).

A trivial use of Helmholtz resonator, known since antiquity and used in medieval and modern times, is the amplification of sound. However, the high position of the pots excludes this use. There remain two possibilities, a symbolic one (developed in [16]) and another acoustic one. We explored this last path and tried to collect evidence.

Thus, the present survey is consistent with an acoustical purpose of the pots in order to provide absorption and hence reduction of reverberation time. But it should be stressed that it only applies to French churches as measured in their present condition. In the past, furniture, such as tapestries, wooden panels or painting, was present in large quantity in churches. It absorbed some of the reverberation. Notice that the pots are tuned at low frequencies for which absorption by furniture is less efficient [16].

4.3. Statistical study of resonance frequencies

4.3.1. Resonance frequency and pot choice

Focusing on the churches selected in Table II, we see that the majority of the pots have a resonance frequency between 100 Hz and 500 Hz, which corresponds to the frequency range where the human voice is strongest (long term statistics [43, 44]). These frequencies correspond to the fundamental or the first harmonics of the singing voice. However, the spread is very large as shown in Table II. A more detailed analysis shows that the mean resonance frequency of the pots decreases as the church volume increases (Figure 9).

When the curve is compared with the Schroeder frequency (estimated from the results of two independent studies of church reverberation times as a function of their volumes [41, 45]), it is surprising to note that the mean resonance frequencies of the pots track at about 3 times the Schroeder frequency, that is, they are well above the Schroeder frequency, considered as the lower limit of diffuse sound fields (thin dashed line). Thus, the pots seem to be in the frequency range of the diffuse field, close to the bands where reverberation times generally are longest.

This finding is consistent with the observations of other authors who have researched large-scale pot systems [4, 9, 12]. The pots would thus appear to decrease the reverberation time at those frequencies which are strongly excited by the spoken voice.

The sound source, mainly the voice in medieval times, does not seem to be the only parameter determining the choice of the pots. The characteristics of the church and "its sonority" – or spectral response – seem also to be taken

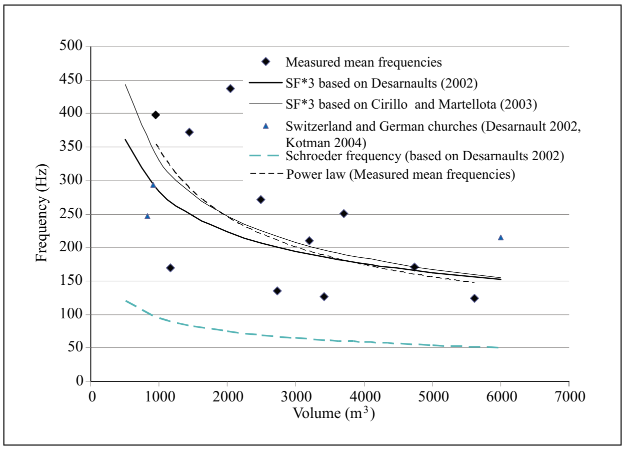

Figure 9. Mean resonance frequency of the pots as a function of church volume. Black dashed line models power law. Full lines represent 3 times the Schroeder frequency f_S calculated with reverberation times from previous studies [41, 45]. Thin dashed line is the Schroeder frequency from Desarnaults [41].

into account. This observation suggests that the control of the sound at low frequencies was the intention of those who inserted the pots, often at later time than construction, and was probably understood by empirical methods. The device usefully complements the effect of furniture at high frequencies, which is better known.

This double constraint (voice and "sonority" of the church) seems to be confirmed by the presence of more than just a single type of pot in numerous churches. In this case, they are often tuned a fourth or a fifth apart, (see Table II). Two or more pot types make it possible to extend the useful frequency band. Moreover, this ratio is similar to the recommendations of Vitruvius concerning the *echea* [3], and we know that Vitruvius was known and intensively commented on during the Middle Ages [16, 46]. So this ratio is probably not an accident in church architecture. Futhermore, octave, fifth, and fourth were important intervals in the music theory of the time, as it was largely inspired by the music theory of Antiquity [30].

5. Discussion

The connection between Vitruvius's vases and medieval acoustic pots suggested by numerous authors between Antiquity and the Middle Ages cannot be made on acoustic grounds only. Indeed, acoustics pots are not restricted to the science of sound. They address other disciplines, such as liturgy, religious iconography, and archeology, all of which are developed in [16]. The present paper, however, is restricted to acoustical aspects.

From the acoustical point of view, many elements differentiate the *echea* of the Greek theatres and the acoustic pots placed in medieval churches. The Greek theatre is an open space, where the search for amplification of the sound can be justified, but has no need for reverberation control. Conversely, medieval churches constitute closed spaces and the sound inside is governed by the laws of room acoustics.

Another important difference is that the devices described by Vitruvius, bronze vases, were placed in niches so they could freely vibrate inside their stone housing. The medieval acoustic pots, inserted in the vaults and walls, are generally embedded in masonry, and consequently they cannot vibrate freely like the devices described by Vitruvius. Thus, their acoustic behaviour is not based on the structural vibration of the device, but on the volume of the air included in the pots.

The question of the number of devices also distinguishes the ancient *echea* from the medieval pots. Whilst the number of the bronze vases in the theatres is precisely determined according to Vitruvius, the number of pots inserted in the walls and the vaults of the churches is very variable.

However, although the ancient *echea* have little similarity, in term of acoustics, with the medieval pots, attentive reading of the text of Vitruvius yields two essential teachings for our research. First, earthen pots were already present in the walls of certain buildings (theatres and temples) in the 1st century BC, and secondly, his writtings probably influenced the architects and the builders in the Middle Ages, to take account of acoustics during the construction of religious buildings. We do know that at least 30 manuscripts of *De Architectura* existed in the medieval monastic library, and that his reading was recommended by many authors [46]. More specifically, Albertus Magnus and Thomas Aquinas used the *De Architectura* to comment Aristotle, even though none of these comments concerns Aristotle's theory of sound. Therefore, an affiliation between Vitruvius's *echea* and the medieval acoustic pots is very likely, and particular support for this is the finding that, when two types of pots are present in the walls of a church, they are often tuned a fourth or a fifth apart [47], as recommended by Vitruvius for the *echea*.

6. Conclusion

Although the phenomenon of acoustic pots is very widespread throughout Europe, it distribution is very disparate from one country to another (see Figure 3), and most of the available research concerns French churches. Definite conclusions are difficult because of the lack of extensive research, even though the majority of authors are convinced that an acoustic intention was present at the time of installing the devices. But regularities in the resonance frequency, as documented in this study, also suggest that the builders, or those who inserted the pots at later times, had some empirical knowledge of acoustic [38].

Indeed, the main result of this study is that the acoustic pots were inserted according to empirical rules during medieval and more modern times. Although the effects are often difficult to perceive just as in modern buildings, the indication from the present survey is that the results are not mere chance: the number of pots increases with the church volume; and the mean resonance frequency decreases with church volume, remaining close to the frequency bands where reverberation times generally are longest.

Thus, all the evidence from the buildings which are preserved today are coherent with an empirical compromise between improving the sonority of the churches and providing good speech perception. But it remains an impossible task to prove this acoustical intention, as there is no survivor of those times to ask.

The only conclusions which we can draw from this short survey is that the purpose of "aerum vasis", as described by Vitruvius in ancient Greek theatres, is still an open question for specialists of antiquity, and that their link to medieval pots remains another open question. What stands out firmly, however, is that Vitruvius provides evidence that pots were already inserted in Roman walls in the first century B.C.

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