Anderson, Barbieri, Baumann, Bisson, Bonsi
Bryant, Callegaro, Cooper, Fenlon, Gaio
Glixon, Guerra, Hopkins, Howard, Moretti
Ongaro, Orlowski, Quaranta, Trentini

Architettura e musica
nella Venezia del Rinascimento

A cura di Deborah Howard e Laura Moretti
The State of Architectural Acoustics
in the Late Renaissance

Patrizio Barbieri

During the Renaissance, the physical schematisation of acoustics could approximately be defined as ‘undulatory’, since it was entirely based on Aristotelian-Stoic theories and on the indications of Vitruvius’ De architectura. These four descriptive indicators, classifying various spaces acoustically, were employed—by way of example—at the beginning of the Cinquecento to design the first music room of the modern age, in the palace of Alvise Comaro, at Padua. Of these indicators, the one concerning the ‘circulation’ of the spherical sound wave was considered especially important. It was thought applicable even to the rounded layouts of the cavea of the first Renaissance theatres. The indicator relating to ‘circumsonantia’ on the other hand was more widely taken into account in church ceilings, in which a rigid distinction persisted between stone vaults (advised for chapels, where music was performed) and wooden coffered ceilings (whose shorter reverberation time made homilies more intelligible, for which reason they were generally preferred by the Jesuits). The various opinions of architects on this subject are analysed; they were rarely, however, based on valid scientific grounds. The connections between organ-stop design, church volume, and the evolution of musical practice is also examined. At the very end of the period, starting from the so-called ‘Scientific Revolution’, a new physical approach to the science of sound was formulated: ‘optical’ or ‘geometrical’ acoustics was born. Physicists thus became aware of the focusing power of curved surfaces, especially elliptical ones, and applied them chiefly in theatres.
1. Before and after the Scientific Revolution: 
Undulatory vs Geometrical Acoustics

Following a model that goes back to Chrysippus (third century BC) and at least up to the late Cinquecento, sound propagation was associated with the motion of circular waves generated by dropping a pebble in a reservoir. In the late first century BC, Vitruvius states that such waves are actually spherical, thereby justifying the hollow cavea of Graeco-Roman theatres.

Modern wave acoustics had not yet been reached, however, since the idea lacked the fundamental concept of wavelength, which was only advanced as late as 1672 by the Jesuit Ignace-Gaston Pardies and formalised by Isaac Newton in 1687 (Shapiro 1973, pp. 136, 139; Dostrovsky 1975, p. 192; Barbieri 2006, § 7.2). It is therefore preferable to refer to the Renaissance science of sound simply as ‘undulatory’ acoustics. In the final decades of the sixteenth century, with the rediscovery of conic sections and the study of concave ‘burning glasses’ (thought to have been used by Archimedes for reflecting the sun’s rays and setting fire to the Roman warships besieging Syracuse), a radical change occurred in the earlier conceptual framework: the propagation of sound was associated with that of light rays, whose trajectories had already been known for centuries. This led to the birth of geometrical acoustics and thus to the first attempts at focusing sound and modifying the shape of the auditorium.

The first person to conjecture the existence of a relationship between light in the burning glasses and sound was Ettore Ausonio, a doctor and mathematician working in Venice in the second half of the sixteenth century; no work by him on the subject, however, has survived. He was soon followed by the Neapolitan scientist Giovanni Battista Della Porta (1589), who claimed that to hear a distant person speaking softly it was sufficient to place the ear at the point of a concave mirror where light was concentrated.

All these new ideas were systematised and expanded by the Jesuit Giuseppe Biancani, who in 1620 founded a new branch of the physico-mathematical disciplines, which he called Echometria.
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(i.e. the geometric description of sound reflections). The *Echometria* in turn ended up as a section of a further branch that—after a slow process over fifteen years, between 1642 and 1657—was officially designated *Acoustica* (Gouk 2001, p. 51; Barbieri 2006, § 2.1). In his work, Biancani analysed several kinds of acoustic reflector, including those of cylindrical shape, which he stated were adopted in the ancient theatres.

Christoph Grienberger, a fellow Jesuit charged with examining the work before its printing, mentions in his manuscript report that he was aware that a theatre of this kind had actually been built in Paris (Grienberger 1619–20, f. 108r). Although he does not reveal its identity, this theatre could have been the one at the Tuileries.

Starting from the late seventeenth century, geometrical acoustics was almost exclusively applied to theatres. In sacred edifices, it is only mentioned in 1639, when Borromini adopted an elliptical layout—for declaredly acoustic reasons, though wrongly understood—for the refectory of the Oratorians at the Chiesa Nuova (S. Maria in Vallicella), in Rome (Barbieri 1998, p. 273). The present paper will thus deal only with Vitruvian acoustics, since the later evolution of this discipline had not yet found practical application by architects at this particular historical period.

2. Vitruvius and Alberti: the Four Subjective Attributes of Acoustic Quality

Until at least the end of the seventeenth century, the only quality indicators of an acoustic space continued to be the four mentioned by Vitruvius. These indicators were subjective, and not numerical, as the modern ones are. According to the interpretation given by theorists of the time (Vitruvius 1567, pp. 259–60; Doni 1763, vol. II, p. 138), these spaces could consequently be:

—*Dissonantes* (= *cata-chontes*), when the wave is affected by a hard and sharp-cornered architectural element: being partly reflected, it disturbs the ‘circulation’ (i.e. the circular diffusion) of
the subsequent wave, so that the sound is ‘dissipated’ and also sounds ‘indistinct’ (meaning something similar to destructive interference).

—Con-sonantes, when, on the contrary, the environment facilitates the wave’s ‘circulation’ (in this case with maximum clarity and intelligibility).

—Circum-sonantes, when the wave (bombo), in the presence of a curved surface, returns to its starting point, creating a reverberation (rim-bombo).

—Re-sonantes, when it is actually reflected back on itself, giving rise to an echo.

A typical example of dissonantes elements can be found in the boxes of Italian opera houses, which—as a famous architectural theorist states in the late Settecento—with their ‘molteplicità di fori e di tramezzi, tagliano in mille guise l’aria sonora, la riverberano in infiniti varissimi sensi, e la debbono per necessità confondere’ (multiplicity of holes and partitions, cut the sound wave in a thousand ways, making it reverberate in an infinite variety of directions, and necessarily rendering it indistinct) (Milizia 1794, pp. 89–90).

Even the over-elaborate bas-reliefs placed on box fronts were accused of impeding the circulation of sound and ‘rompe qui vi la voce’ (breaks the spherical wave), with the result that—starting from the late Settecento—it became customary to decorate them only with pictures, so that ‘la voce più facilmente scorra’ (the voice could slide more freely) (Barbieri 1998, p. 284). The persistence of this belief can be explained by inadequate knowledge of the mechanisms of diffraction, diffusion and absorption.

Examples of consonantes spaces on the other hand were the Graeco-Roman theatres and those of the Renaissance with their curvilinear cavea (inspired by the classic model, although the addition of a roof made the environment less ‘dead’). This is confirmed by the inauguration of the Teatro Olimpico at Vicenza, which took place in 1585 with a performance of Sophocles’s Oedipus Rex, complete with two- to six-voice choruses by Andrea Gabrieli: though the chorus was made up of fifteen singers
in all, a report from the same year found it necessary to mention that ‘s’intendevano schiattamente le parole quasi tutte’ (nearly all the words could be perfectly understood) (Mancini 1985, vol. II, p. 225). Likewise, in order to improve the consonantia, in a sketch for a speaker’s hall Leonardo da Vinci went so far as to make the orator speak from the top of a column, right in the centre of a 360° spherical cavea (Forsyth 1985, p. 14).

An example of the external closure of an environment with an element that was not resonans was provided by the gallery (portico) that enclosed the top of the cavea (figure 1). Unlike what

would have happened with a flat surrounding wall, Leon Battista Alberti (1447–52) observed that the soundwave was collected in this gallery, where—being softly received into ‘densatus illic aer’ (much thicker air)—it was not reverberated thence too violently, but returned clear and somewhat strengthened (Alberti 1966, vol. II, p. 741).

To increase the short reverberation time of open-air theatres, another method was the use of Vitruvian vases (echeia), visible immediately below the gallery (figure 1), about whose actual contribution Alberti appeared to be rather sceptical (Alberti 1966, vol. II, p. 745). They were adopted however by Francesco di Giorgio Martini (c. 1478–81), but with a different purpose (figure 2): with them he built up a kind of ‘wave guide’, under the illusion that the sound would better reach ‘the ears’ of the audience sitting in the highest seats (Martini 1967, pp. 256–7). His fanciful historical reconstruction—made up of a chain of two kinds of resonator, one of which is similar to the resonator that today bears the name of Helmholtz—has, however, the status of being perhaps the first acoustic device invented in the modern era. In the following century, the echeia enjoyed renewed interest, thanks also to the discovery—by the native of Vicenza, Onorio Belli (1586), in the ruins of the Greek theatres on the island of Crete—of the cells in which they were formerly lodged (Puppi 1973, pp. 92–3).

According to the diary of John Evelyn (1645), ‘urnes and earthen potts for the better sounding’ (=echeia) were, by way of example, present in the music room of the palace of Alvise Cornaro, at Padua (Evelyn 1955, vol. II, p. 467). This room (odeo), still extant, was designed in c. 1524–30 by Giovan Maria Falconetto, an architect friend of Cornaro. In the rest of its configuration, too, this auditorium fully obeyed the prescriptions of Vitruvius and Alberti (figure 3); indeed, Sebastiano Serlio (1475–1544)—following Alberti’s observations already mentioned—says that it was very well suited to music, owing to its shape ‘che tende alla roondità’ (which tends to rotundity) and because it was equipped with ‘li quattro nicchij [che] per la sua ritondità concava ricevono le voci,
et le ritengono’ (four niches which, owing to their concave rotundity receive the voices and retain them) (Serlio 1584, vol. VII, p. 218). These niches therefore acted as authentic sound diffusers.

The ‘round’ rooms, which as we have seen were deemed to be rather suitable for music, were, however, considered unfavourable for the intelligibility of the spoken word. This was due to the third of the Vitruvian acoustic parameters: circumsonantia. The origin of this prejudice can in all probability be found in Alberti, who—in illustrating the two Vitruvian curiae, sacerdotum (covered with a vault) and senatoria (provided with a flat wooden ceiling)—observes: ‘Erit igitur sacerdotum curia testudinata, senatoria vero curia operta contignatione. In utrisque rogati consultatores, verba habituri sunt, vocum idcirco ratio habenda est. Adesse ea de
3. Padua, music room (p = ‘salotto’) of the palace of Alvise Cornaro. In the original, the plan and elevation are on two different pages. The fire that can be seen in the basement served to heat the room through the floor, ‘as was the ancient custom’: a fireplace in the room—Serlio explains—would have threatened to crack the soundboards of the stringed instruments due to excessive dryness of the air (from Serlio 1584, vol. II, pp. 219, 223)

re oportet, quod vocem non sinat altius diffluere, et maxime in testudine, nequid durius in aurem retonet. Venustatis nimirum atque in primis utilitatis gratia coronae parietibus appingentur [my italics]’ (The sacerdotum curia is thus covered by a vault, and the senatoria curia by coffers. In both, the officials have to respond to questions, for which reason care must be taken with the acoustics. It is therefore best to ensure that the voice is not dis-
persed upwards, and *especially in the vault*, to avoid unpleasant reverberations on the ear. For ornamentation, and particularly for their usefulness, cornices are applied to the walls [my italics]) (Alberti 1966, vol. II, p. 759) (figure 4).

Thus Alberti—following Vitruvius—in his plans for the *curiae* suggests placing a cornice mid way up the perimeter walls, to prevent the orator’s voice from dispersing upwards and thereby producing *circumsonantia*. From figure 4, however, we see that the underlying niches, acting as sound diffusers, must have made a decisive contribution. Hence, when assessing the proliferation of ‘Vitruvian’ cornices during the Renaissance, it is worth remembering that this acoustic function was also attributed to them. In 1544, for example, Guglielmo Philander expressly cited acoustic motivations for the insertion of cornices in choir stalls and preachers’ pulpits (Barbieri 1998, p. 267).

Even today, however, no quantitative surveys have demonstrated their effective acoustic function. From an experiment carried out by the Jesuit Daniello Bartoli (1608–85) in the famous ‘camera parlante’ (whispering room) at Palazzo Farnese at Caprarola, it was found that the existing cornice (merely projecting by one palm’s span) was insufficient to block the whispered words creeping along the wall; these managed to reach the top of the vault, where they could be distinctly heard by a person made to climb up there on a ladder (Bartoli 1679, pp. 102–6). More recent experiments, conducted in other ‘whispering places’, have however ascertained that architectural elements that project sufficiently succeed in impeding the voices in question from creeping along the walls, since being whispered they are mainly composed of high frequencies (Glover 1933, p. 144).

3. The Dilemma of ‘Sound’ Churches:
Vaults & Domes vs Coffered Ceilings

We now come to further practical repercussions of the theories examined in the previous section. For the very same acoustic rea-
4. Reconstruction of the Vitruvian sacerdotum curiae. In the original, the plan and elevation are on two different pages (from Alberti 1966, vol. II, pp. 760–1)

sons, in his famous memorandum for the Venetian church of S. Francesco della Vigna (1535), Francesco Zorzi prescribes that the chapels and chancel should be covered by vaults, whereas in the nave on the other hand—where sermons are preached—he required a flat wooden ceiling (a travatura) with coffers as deep as
possible (Howard 1975, p. 70; Foscarini 1983, p. 210). The acoustics of the no longer extant church of the Ospedale degli Incurabili (Venice, end of the sixteenth century) were always judged to be paradigmatic, especially owing to its flat wooden ceiling. Furthermore, its rectangular layout with rounded corners and walls lacking any architectural discontinuity were deemed to have been designed to facilitate the Vitruvian circulation of sound (Bassi 1963, p. 53; Aikema 1989, pp. 132–6). The same arrangement is also found in the music room of the Ospedalletto, dating from 1776 (Aikema 1989, pp. 166–7).

The rounding of corners—even of the sharp corners inside boxes, deemed responsible for ‘divorare il suono’ (devouring the sound)—in seventeenth- and eighteenth-century theatres is often recommended on acoustic grounds (Barbieri 1998, p. 283).

In the second half of the sixteenth century, with the Counter Reformation, the new emphasis on preaching led to the widespread use of coffered ceilings (Howard 1975, p. 70). An exemplary case is the church of the Gesù, in Rome (1567–8). It was for this very reason that the general of the Jesuits and the company’s architect, Giovanni Tristano, wanted a coffered ceiling; of the opposite opinion, on the other hand, was Cardinal Alessandro Farnese, who in the end—in a strong position as sponsor of the enterprise—ordered Vignola to cover the church’s single nave with a barrel vault (Pecchioli 1952, pp. 54–6; Pirri 1955, p. 228). In the very same months, in Milan, the church of S. Fedele was being designed with a vaulted ceiling; Pellegrino Tibaldi, the favourite architect of St Carlo Borromeo, knew however that for Tristano ‘non piacciono le chiese tonde’ (he did not like rounded churches), and consequently feared that he would reject the project. In December 1567, therefore, he suggested to Tristano ‘che questo architetto [= Tibaldi] l’assicura, che questa chiesa è in miglior forma che si possa desiderar per predicare, et che non impedirà punto la voce, sì per essere interrotta in molti luoghi, come per li molti fori che haverà’ (that this architect [= Tibaldi] assures you that this church has the best shape that can be desired for preaching, and will not hinder the voice in any way, owing both to the
breaks in many places and to the many openings it will have) (Pirri 1955, pp. 147, 165, 171, 226–7).

Similar considerations are found later in Vincenzo Scamozzi (1615), who even claimed—and this in express disagreement with the common belief—that the acoustics of a building are helped by the use of vaults and, above all, domes: provided, that is, that the internal walls are broken up as far as possible by cornices (preferably two superimposed orders), openings, coffers, cavities, reliefs and pilasters. Though he does not say as much, all of these features are found in the Pantheon in Rome, a building with which Scamozzi was very familiar, since it had been illustrated in Serlio’s treatise, partly edited by his father (Serlio 1584, vol. III, p. 52). Instead, the example he actually uses is the Vatican basilica of St Peter’s, whose good acoustics he attributes precisely to these expedients (an opinion that has turned out to be correct, as an acoustical survey carried out in 1964–70 confirmed: Shankland 1971). To bear out the validity of his theories he then refers to the church of S. Giustina at Padua, where he claims to have improved the acoustics by dismantling six bowl-shaped vaults and thus opening the pre-existing superimposed domes (figure 5); however, even taking into account the evidence of Giordano Riccati (1788), the real extent of his remodelling is not at all clear (Scamozzi 1615, vol. II, p. 326; Barbieri 1992, p. 303).

In the following century, the architect Francesco Maria Preti also affirms that the dome he designed for S. Liberale, at Castelfranco Veneto (1724–46), was found very suitable for eliminating the church’s defect of ‘soverchia sonorità’ (excessive sonority) (Preti 1780, p. 36). In figure 6 it can be seen, however, that it was a false dome: the thin lower catino, together with the air contained in the interspace, must have acted as an absorber of low frequencies, thus reducing reverberation (but not sufficiently, as we shall see in §4). At the same time, this was the solution then adopted in Italian opera houses, where the ceiling was made of reed lathing or plastered canvas hung from the roof above. Of this absorption effect explicit mention is made, however, in only one document of the late Settecento, relating to a theatre at Pi-
5. Cross-section of the church of S. Giustina, Padua, by F. M. Preti, 1766
(from Kilian 1997, p. 440, detail)

6. F.M. Preti, design for the cathedral at Castelfranco Veneto, 1753
(from Puppi 1990, p. 155, detail)
stoia: ‘Per soffitta in tutti i teatri suol praticarsi un’incannicciata che non rimbomba quanto una volta, nè assorbe la voce come la nostra tela [non intonacata]’ (For all theatre ceilings, the custom is to use reed lathing, which does not reverberate like a [stone] vault, nor does it absorb the voice like our [unplastered] canvas) (Chiappelli 1913, pp. 267–8).

This type of covering had already been advised by Alvise Cornaro for the chapels in the basilica of S. Antonio (c. 1550), but for the purpose of lightening the weight on the supporting walls (Fiocco 1965, p. 155). He does, however, mention their excellent acoustic rendering, when he speaks of the ‘volto fatto sopra il choro di S. Giorgio maggiore di Venezia il quale è di cannavera, et è molto bello et sonoro, che le voci rispondono in esso perfettamente’ (vault constructed over the choir of S. Giorgio Maggiore in Venice, which is of reed lathing, and is very handsome and resonant, so that voices can be heard perfectly there). The very same material had been used, he adds, in the vault of the Cappella del Santo at the basilica of S. Antonio in Padua.

4. Organ Intonation and Church Acoustics

4.1. Intonation. In adapting their instruments to the size of the churches for which they were destined, organ-builders have always taken into special account the length-diameter ratio of the pipes. The smaller the ratio, the squatter are the pipes: thus the more preponderant the fundamental frequency as compared to the overtones, so that the sound gains in body and loses in transparency.

This ratio is connected to the aesthetic ideal found at various eras. For the average pipes, in the Middle Ages the value adopted was very low, around 8:1 (Mahrenholz 1975, pp. 31, 34). This value is in good agreement with those reported by Giorgio Anselmi in 1434. Anselmi himself specifies that—in small churches—organ-builders adopted higher ratios (as great as 9:1), so as to obtain a ‘suavis et mediocris’ (sweet and moderate) sound; in large basili-
cas, on the contrary, the ratio was as low as 7.5:1 or even 7:1, with a sound that was ‘asper et perstrepens’ (harsh and loud) (Anselmi 1961, pp. 140–1; figure 8).

Probably with the aim of giving greater clarity to polyphony, starting at least from the second half of the 15th century these ratios roughly doubled, becoming around 18:1 for the standard front pipes (figure 8): see the organs of St Petronio in Bologna (c. 1475) and of St John Lateran in Rome (1598, by Luca Blasi). According to a contemporary drawing (figure 7), still higher ratios were found in the so-called organ ‘of pope Alexander VI’, once in the Vatican basilica of St Peter’s (1496). With this solution the emission gained ‘piuttosto che il fragore la dolcezza’ (sweetness rather than thunder), as stated by an organmaker in 1852, referring to Blasi’s instrument (Luccichenti 1994, p. 94). This also produced difficulties, as in the organ built by Giovanni Battista Facchetti for the cathedral of Cremona (1542–4), judged insufficient by Giovanni Maria Lanfranco for a crowded church, because ‘il Maestro ha avvertito più alla dolcezza che alla crudezza’ (the Maestro paid more attention to sweetness than to loudness) (Manzin 1985, p. 13). The tendency to lighten the emission by reinforcing the overtones finds confirmation in the organ designed by Nicolò Tezano for the Roman church of the SS. XII Apostoli (1549). In his contract—besides promising a ‘dolce e argentino’ (sweet and silvery) sound—he states that he would have to double the high range pipes in the Octave stop ‘per essere la chiesa grande’ (owing to the large size of the church) (Barbieri 2005, appendix 2).

The debate between the relative merits of vaults and flat coffered ceilings, already discussed, came high in the organ-makers’ considerations. Antonio Barcotto, active in Padua in 1652, says: ‘È da sapere, che nel situar organi, si deve prima considerare, se il suffitto della chiesa è fatto a volto, e di che grandezza è la chiesa, poiché se la chiesa sarà grande, e il suffitto di asse, ricercherà organo di maggiore voce e più sonoro; e se la chiesa a volto, l’organo deve essere un poco più dolce, e di manco forza, poiché il
7. Rome, old St Peter’s, organ ‘of Pope Alexander VI’, 1496
(from Lunelli 1958, plate V, detail)

8. Five Italian organ pipes, front Principale stop, all producing the same note
(length-diameter ratio, end-correction added). 7:1 (1434, Anselmi: large churches),
9:1 (1434, Anselmi: small churches), 18:1 (Bologna, S. Petronio, Lorenzo da
Prato organ, 1475; Rome, S. Giovanni in Laterano, Luca Blasi organ, 1598), 28:1
(modern Viola da gamba stop, similar to some of the 1496 front pipes
represented in figure 7), 11:1 (Treviso, S. Teonisto, Gaetano Callido organ, 1781)
volto forma l'eco, e dà forza alla voce’ (In the positioning of organs, we must note whether the ceiling of the church is vaulted and consider the size of the church, because if the church is big and the ceiling of wood, an organ of greater voice and sonority will be needed; if the church is vaulted, the organ must be a little sweeter and not so strong, since the vault forms an echo and strengthens its sound) (Lunelli 1953, pp. 154–5). In the Settecento, both the number of stops and sound emission were boosted, especially in the Veneto region, where for the front Principale low ratios—almost as low as those used in the early Quattrocento—began to be generally adopted (starting from Pietro Nacchini and Gaetano Callido, see figure 8).

The architect Francesco Maria Preti—in his design for the internal restoration of the basilica of S. Antonio, at Padua (1749–50)—observed that the volume of sound from the two new organs was too ‘audace’ (bold), adding that ‘nella cappella vecchia era-vene due soli di Vincenzo Colombo l’uno, e l’altro di Vincenzo Colonna, e questi di soli dieci registri. E siccome questi due auttori facevano un’armonia assai quieta, così reputo, che la musica riuscisse à maraviglia in confronto di quella, che presentemente facciamo. Per li concerti eravi un organo portatile, e ciò perché a que’ tempi non erano in uso tanti stromenti, nè si solea fare quel sussurro [= baccano], che oggi si fà’ (in the old chapel there had only been two, one by Vincenzo Colombo and the other by Vincenzo Colonna, and these had only ten stops. And since these two builders made a rather quiet harmony, so I deem that the music succeeded marvellously as compared to what we do now. For concertato pieces there was a portable organ, and that was because at that time so many instruments were not in use, neither was it customary to make such an uproar as they do nowadays) (Puppi 1990, p. 227).

We must consequently infer that the acoustics of a given space, judged adequate for Renaissance music, could be deemed no longer suitable in later centuries, when sound emission increased in volume. For this reason, today, it is very important to conform to the original performance prescriptions.
4.2. Acoustic corrections and standing waves. In the event of excessively long reverberation time, interventions aimed at increasing the ratio of direct to reflected sound. This was obtained 1) by lowering the organ loft, and/or 2) by stretching over the case fabric that would absorb the waves directed upwards. In connexion with this second point, Geminiano Montanari, professor of mathematics at Padua, as early as 1678 confirmed that ‘s’adattano sopra i pulpiti delle chiese troppo grandi, le tele, che riportano l’eco a riunirsi in tempo con la voce primaria’ (they fit drapes over the pulpit, in churches that are too large, in order not to have a too great delay between the direct and reflected sound) (Montanari 1696, p. 253). Actually the drapes were absorbing (and not reflecting) the waves directed upwards.

The lowering of the organ-lofts was, for example, carried out in 1640 at Padua, in the church of S. Giustina (figure 9): this suggests that the acoustic intervention of Vincenzo Scamozzini, mentioned in § 3, had been found inadequate (Organo 1973, p. 17). For similar reasons, the acoustician Giordano Riccati lowered the lofts of the cathedral at Castelfranco Veneto (S. Liberale), leading us to believe that in this case, too, the dome by Francesco Maria Preti was found wanting in this regard (§ 3). Again, in 1788, Riccati advised a similar intervention in the loft of the cathedral at Chioggia: in this way, he affirmed—recalling that that a wave’s intensity is inversely proportional to the square of the path covered—the direct waves would be strengthened to the extent of masking the reflected ones, further weakened and delayed by the increased path (Barbieri 1992, pp. 301–3).

Another case in this connection is that of S. Maria della Pietà, in Venice. Rebuilt in 1745–60 on a layout with rounded corners similar to the one at the Incurabili, unlike the latter it was provided with a vaulted ceiling, which—invoking acoustic grounds—had already been opposed in a report made in 1742 by the mathematicians Giovanni Poleni and Bernardino Zendrini. When the building was completed, the reverberation time was confirmed as being excessive (Bassi 1963, pp. 53–4). Giuseppe Sarti—
the new *maestro di cappella*, who was also interested in acoustics on an amateur basis—had the organ voiced anew in 1766, so as to ‘mitigate’ its emission by making the pipes speak more softly (it had been built by Pietro Nacchini in 1759). Since this was not sufficient, in 1770 the acoustics were considerably improved by inserting a canvas cloth that had been lent to the church, resulting in the proposal to purchase as much as 700 *braccia* (almost 480 metres) of canvas to stretch over the lofts during musical performances (Vio 1978, pp. 188–90; Dalla Libera 1962, pp. 93–4). According to Riccati (1788), even this intervention was in-
sufficient, an observation indirectly confirmed by the fact that the organ was voiced again in 1773 (Barbieri 1992, p. 303).

The large pieces of canvas installed in S. Petronio in Bologna in 1722, must have served the same purpose (figure 10); it appears, however, that practical tests carried out in 1986–91 produced ‘no audible effect’ on the church’s long reverberation time (Vanscheeuwijk 2003, p. 64). A late example of similar acoustic treatment was carried out at the enormous Royal Albert Hall in London (1871), an auditorium with excessive reverberation time and a pronounced echo: the latter was produced by the great dome, whose centre of curvature is close to the level of the stalls. This inconvenience was eliminated by fitting acoustic reflectors and more especially by hanging beneath it a great drape, performing the same service as the cloths mentioned above (Knudsen 1932, pp. 540–1).
The problem of dome acoustics—long debated by Alberti, Vitruvius and the architects of the Renaissance, as we have seen—was therefore only solved later on, on the basis of geometrical acoustics. It should also be remembered that reflexions by vaults and walls also produce undesirable 'standing waves', already complained of by Theodore Deschamps in a letter dated 1642, in which he reports that 'cette voix, qui se forme par reflexion dans les choeurs des églises et en certains instruments, importunant l'oreille des chantres, s'entend à la douziesme de celle qu'on chante, et non à l'octave' (this sound, produced by reflection in church chancels and in certain instruments, vexing the singers' hearing, is heard at the twelfth of what is sung, and not at the octave) (Mersenne 1967, p. 614).

Even in more recent times, in the church of S. Petronio in Bologna, standing waves have been reported by musicians, in this case corresponding not to the third, however, but to the fifth harmonic (Vanscheeuwijk 2003, p. 64).

5. Conclusions

The so-called 'undulatory' approach to acoustics—based on Aristotelian-Stoic theories and on the four subjective quality-indicators of Vitruvius—was sufficient only for treating open spaces, like the Graeco-Roman theatres. It showed its limitations when applied, during the Renaissance, to the acoustical design of closed spaces. For the latter, a knowledge of the physics of sound was needed, in particular, the concepts of 1) focusing, 2) diffraction and diffusion, 3) absorption (also by materials mixed together, like in the resonators formed by panels coupled to confined air).

The focusing of sound only began to be considered at the end of the Renaissance (during the 'Scientific Revolution'), with the introduction of 'optical' or 'geometrical' acoustics. Full understanding of the physical parameters 2 and 3 would only be achieved in the later 19th century. Renaissance architects were thus totally unable to cope scientifically even with very simple rooms,
let alone the vexed question of ‘round churches’ (i.e. domes and vaults). The first quantitative acoustical indicators would not be introduced until the 20th century, and the psycho-acoustical ones have only been considered in recent decades.

Turning to organ design and voicing, it has been shown that these were not only influenced by the church’s internal volume and the materials employed therein, but more especially by the evolution of musical style.

In the period between the mid Quattrocento and the late Cinquecento, a surprising development has been identified: the extremely low length-diameter ratio of the early 15th-century standard organ-pipes was approximately doubled, in order to give more clarity and sweetness to the sound.

Problems of excessive reverberation also arose when, in the following centuries, large organs and large instrumental mechanisms began to be used in churches built at earlier periods. Not until the Baroque period, would acoustical corrections be attempted.

Nel Rinascimento, la schematicizzazione fisica assunta per l’acustica potrebbe grosso modo essere definita “ondulatoria”, dato che si basava interamente sulle teorie aristotelico-stoiche e su quanto riportato nel De architectura di Vitruvio. Di quest’ultimo vennero soprattutto presi in considerazione i quattro descrittori qualitativi con cui classificava acusticamente i vari spazi, che ad esempio furono impiegati all’inizio del Cinquecento per progettare la prima sala da musica dell’epoca moderno: quella del palazzo di Alvise Cornaro, a Padova. Fra tali descrittori, era ritenuto molto importante quello relativo alla “circolazione” dell’onda sferica sonora, che anche nei primi teatri rinascimentali continuò a trovare applicazione nella cavea a pianta rotondeggiante. Quello relativo alla “circumsonanza” trovò invece maggiore impiego nelle coperture delle chiese, dove persisteva una rigida distinzione tra volte lapidee (consigliate per le cappelle, dove venivano eseguite le musiche) e soffitti di legno a cassettoni (il cui minore tempo di reverberazione permetteva invece una migliore intelleggibilità delle ome-
te le diverse opinioni degli architetti a tale riguardo, che quasi mai comunque si dimostrano basate su valide giustificazioni scientifiche. Valutate sono anche le interconnessioni tra progettazione acustica degli organi, volume della chiesa ed evoluzione della pratica musicale. Alla fine del periodo in questione, iniziando dalla cosiddetta “rivoluzione scientifica”, venne formulata una nuova impostazione fisica della teoria del suono: nasceva così l’acustica “ottica” o “geometrica”. I progettisti divennero così consapevoli del potere focalizzante delle superfici curve, soffermandosi specialmente su quelle ellittiche, e le impiegavano soprattutto nei teatri.
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