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Chapter 8

The Evidence of the Use of Sound Resonance from Palaeolithic to Medieval Times

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Many studies have shown that various monuments, from Palaeolithic to medieval times, have resonant qualities. However, almost none of these studies gives any evidence of the awareness or genuine use of these sound qualities by those who constructed the monuments or worshipped in them. What real evidence do we have of the conscious use of resonance in ancient times? Here are given four kinds of evidence which we have studied: two from Palaeolithic caves and two from Antiquity and the Middle Ages.

In recent years many studies have tried to show the resonant qualities of caves, rock formations, temples or megalithic constructions, which are known to have been visited, decorated or constructed by ancient civilizations. Instances include Palaeolithic decorated caves (for a general study see Reznikoff 2002a), rock-art sites (see Waller 1993; Chapter 4 this volume),[1] exteriors and interiors of ancient temples in Mexico (Lubman 1998) or in France,[2] and famous megalithic sites (see Watson & Keating 1999; Chapter 2 this volume). But in most cases the question remains unanswered whether the resonant or sound quality of the studied location was appreciated and used as such in ancient times by contemporary people who constructed, painted or marked it and, hence, certainly celebrated in some way within that location or monument. Nowadays orchestras and musicians dislike strong resonance, because it too easily leads to congestion of sounds, and also because it is incompatible with the modern tempered (non-natural) tuning of musical instruments.[3] But what about ancient civilizations?

Even when the quality of the resonance in a place seems obvious to us and must surely have been known to ancient people also, it does not mean that they used this resonance or even appreciated it, since we do not even know, for certain, whether they sang or celebrated with sounds there. And if we believe that indeed they did so, it is only on the basis of the general argument that in oral traditions people sang for whole days and often all night long, especially when marking important events of life. But this, of course, doesn't prove anything for a given monument: after all, either outside or inside this resonant monument or location contemporary people could have remained silent!

A typical example concerns the resonance of the main chambers of the great Pyramid in Egypt; some experiments — rather *New-Age* in style — were done there, and I have often been asked whether, as a specialist of resonance, I have ever tried to sing there myself. But apart from the delight of simply being there, even if the chambers resonated marvellously, it would not mean that they were constructed for the purpose of sounds, or that such a sound quality was exploited there in some performance or celebration. The same can be said of many of the other studied sites or monuments. For instance, of the various examples given in the well-documented book by P. Devereux (2001), very few studies seem to offer effective evidence of the genuine use of resonance in ancient times.

When a musical *instrument* has been identified as such, it is *de facto* clear that it was used as a musical instrument. However such an identification may sometimes be quite problematic, as was recently demonstrated for prehistoric bone pipes by F. d'Errico (2002), or may remain an open question; for example, it is unclear whether some rhombus-shaped objects in the Upper Palaeolithic should be interpreted as sound producers or as pendants (neck ornaments). Of course the fact that an object produces seemingly worthwhile sounds does not mean that it has been conceived and used as a musical (or simply sound-making) instrument; but in general the identification of a musical

instrument is often straightforward. The problem is harder with natural lithophones, in the Upper Palaeolithic, since they were not built on purpose and it is therefore questionable whether they have been used, even if there are some marks on them, whether man-made marks or 'natural' ones. Moreover, even where such marks really do prove to have a human origin, can we be sure that they relate specifically to sounds? Some marks clearly are man-made (for example in the case of red marks or small pictures on sounding stalactites). This, however, still does not prove musical use: there are such marks elsewhere on non-sounding stones and walls. The evidence does not usually lead to firm conclusions. However, it is perhaps convincing enough (se e.g. Dams 1985; Reznikoff 2002, 46; Ablova 2003).

Completely different is the problem of establishing the use of resonance in natural caves, open spaces with echo effects, or even man-made spaces (temples, churches). Given such a space, how is it possible to show that it was used also for its sound quality, and — to come to the main question — *what real evidence do we have of the conscious use of resonance in ancient times*?

The evidence can be supplied by:

a) written records of the time;
b) marked signs or ornaments that can be proved to relate directly to the resonance of the space considered or at least to some parts of it;
c) (for man-made spaces) special architectural features that are obviously acoustical.

The easiest of these to address are of course (a) and (c). Selected below are four sets of evidence that we have studied; two in Palaeolithic caves (related to point (b)) and two belonging to Classical Antiquity and Medieval times (related to point (c)). Let us first, however, consider point (a).

Ancient literature

Support from ancient literature is unfortunately almost non-existent. For the most ancient times — the Stone Age — there are of course no written sources at all. For later periods, when some rare texts mention what can be understood as resonance or, more explicitly, echo effects, the sources never, as far as I know, relate to a specific extant monument which is known to us, the only exception being the theatre of Epidaurus. For instance, in the ancient tradition of Finland (known from oral traditions transcribed in the nineteenth century as *Vanhat Runot*, Old Verses, or from the famous novel *The Seven Brothers* by A.Kivi) we learn that echoes were often used in open spaces; but where precisely, and how, we are not told.[4]

The most beautiful, dramatic and complete account of the use and awareness of echo can be found in the life of St Germanus of Auxerre (died AD 448) as told in his life, *Vita S. Germani* (III, 17–18) written around 480 by Constantius of Lyon (de Lyon 1965, 155–9) and later recounted by Bede the Venerable in his famous *Historia Ecclesiastica Gentis Anglorum* completed in 731. Germanus was called to Britain to help to evangelize the invaders, actually the pagan Saxons. The British, who are Christians, had to fight hard against them. A battle was prepared, the troops were facing one another. Because the Picts joined the Saxons, the Christians forces were weaker and the outcome appeared likely to be tragic. But they were not weak in spirit and Germanus — known already for a saint — is with them. He gives voice to the triple Easter Alleluia, for indeed it was Eastertide. As Bede writes, 'the whole army joined in this shout, until the surrounding hills echoed with the sound' (Bede, *Hist. Eccles.*, I, 20). At once, the enemy was convinced that there were British troops hidden in the hills all around them. 'The enemy column panicked, thinking that the very rocks and sky were falling on them' (Bede, *Hist. Eccles.*, I, 20). Terrified they fled the battlefield, put to flight by the Easter Alleluia and its echo.

This battle (*c.* AD 429) took place either at Verulam (St Albans, Hertfordshire) or at Mold (Flintshire, Wales).[5] It is very remarkable that the *incipit* of the Easter Alleluia (on the word *alleluia*, before the melisma) sounds very like trumpets of Victory and can indeed be easily shouted out; it sheds light also on how this Alleluia has to be performed: as the song of our Lord's Victory over Death.[6]

Of course there are many other accounts of the use of echo in the ancient literature (e.g. in Ovid's *Metamorphoses* VIII, 10–20), but the one above is, no doubt, the most impressive.

Concerning resonance, probably the oldest text that mentions it clearly, is found in the Life of St Vincent of Saragossa (Spain, end of the third century AD) as related in the *Acta Sanctorum* (on the 22nd of January, i.e., on St Vincent's day) and retold in verse by the poet Prudentius in the 4th century in Spain.[7] During his martyrdom Vincent, after having been tortured, was left alone in a cave; there, after a while, he started to sing, praising the Lord for the marvels of Creation. Prudentius writes: 'to the sweet song of the martyr, as an emulating voice, answered the echo of the concave space'. The guards, listening, heard many voices singing with Vincent; impressed by the beauty of the sounds but wondering who could be singing with the martyr they came and looked but, of course, they found him alone. This happened several times, and in the end they came to the obvious conclusion:

Vincent must be being accompanied by a choir of angels.[8]

This explanation 'by angels' is often referred to in early medieval texts when describing the sound of a voice singing in a church and what appears to be the choir of harmonics heard in the resonance. It occurs, for example, in Bede's *Historia Ecclesiastica Gentis Anglorum*, (IV, 3). Although, as indicated above, we do not know what churches (or cave) were referred to. But it proves, at least, that in those times people were aware of and did marvel at the quality of resonance of their churches. This, as shown below, is confirmed by a much more direct and obvious form of evidence: their architecture (point (c) above). So, to conclude, there is not much information available from the literature before the Renaissance. Let us now turn to point (b) which brings us back to prehistoric times.

Statistics

A meaningful connection between man-made signs and the resonance of a cave (or of an open space in connection with rock-art), can, in my view, be established only on a statistical basis. Only such a systematic study is reliable: if among signs and pictures some are found to correspond to resonant locations, then we can assert this relationship as shown, if the positive connections are statistically significant. Otherwise doubt remains: perhaps the connection appears just by coincidence.

For a statistical study to be effective, it must be based first for a given cave (or space) and then, by collecting several such studies, one might begin a general comparative study of a range of decorated caves (or open spaces). There have been, until now, very little such statistical studies. Some of them, however, have produced very clear results; at Le Portel (Ariège, France), I obtained an estimate of the correlation of 80 per cent and at Niaux (Ariège) of up to 90 per cent, of pictures found in *well resonating* locations; it has to be said, however, that at Niaux almost all the pictures are located in the *Salon Noir*, which has very rich acoustics, like a Romanesque chapel, and therefore, of course, almost all the pictures there are in correspondence with this beautiful resonance (Reznikoff 1987, 155). At Arcy-sur-Cure (Burgundy) the correlation is also very high and can be estimated at more than 80 per cent; in other words, most of the pictures are concentrated in the most resonant parts of the cave (Reznikoff 2002, 48).[9] The values we attach to such estimation depend, of course, on the criteria we choose to define what we mean by a *well-resonating* or *good-sounding* location; so a serious discussion is needed.[10] In some caves, such as Oxocelhaya (Pays Basque), the problem, and therefore the criteria, can be complex; in others the result may depend very much on the criteria chosen — and yet the precise criteria to choose may not be obvious. But even when in a cave there seems to be a high correspondence value some doubt may remain for a particular picture or sign. Given such an individual case, can we be sure that it really was intended to relate to the resonance we hear? It is remarkable that in some cases the answer is in the affirmative. It gives us our first strong evidence.

Red dots in Palaeolithic caves

Among the clearly non-figurative signs often found in prehistoric painted caves are red dots or marks, made of ochre or sometimes of haematite. These dots have a more-or-less round shape, about 1 to 2 cm in diameter. Because of this small size they can be found in various locations, including those where, for some reason, a picture could not be painted: perhaps, for example, because the surface is not smooth enough. Since we can exclude pictorial reasons for marking such dots in particular places the question arises as to why they might have been painted where they are. For example, in a long narrow tunnel where one has to crawl, one may find an isolated red dot appearing suddenly on the roof or side wall, whereas there was neither one before that point nor after it, and no other paintings appear to be present at all. What rationale can be given to explain such a situation? An answer is given by the remarkable relationship between such dots and the sound qualities of their locations. As a general rule, *the red dots or marks are related closely to the resonance of the part of the cave where they are located.*

This result, which we reported in 1983 (Reznikoff 1987, 309; Reznikoff & Dauvois 1988, 241 & 244),[11] has received clear verification in some narrow recesses or tunnels (*boyau* in French). In two of these tunnels, one of approximately 6-metre length at Oxocelhaya and one of some 10 metres at Le Portel, a red dot appears at the very location of maximum resonance. Such dots can be found by blind trial in which the investigator, progressing through the tunnel in darkness, puts on the light when maximum resonance is reached and inspects the walls: the red dot is there. Since (1) there is apparently no other reason for painting the dot where it is and (2) the correspondence with the point of maximum resonance is precise, the conclusion, as astonishing as it may seem, is straightforward: the red dots have a sound-resonant meaning. As to probability: if one admits a possible margin of inaccuracy of, say, 10cm for the location of maximum resonance, the likelihood of locating the dot accidentally at the right location would be 100 to 1 for a tunnel 10 m long and 60 to 1 for one 6 m long. This yields odds for

both tunnels combined of 6000 to 1. But at Le Portel, at Oxocelhaya and in other caves, there are other red dots too: one of them in a part of a 10-metre gallery and many others in smaller locations, which still correspond to maxima of resonance, although not in such a spectacular way as I have described above. Considering several locations together, the odds of all these correspondences having come about purely by chance would reduce to something of the order of a million to one. These are very long odds. When we add to them the apparent absence of any other rational explanation, the acoustic meaning of such signs begins to appear very convincing indeed.

Of course, prehistoric people were not studying the acoustics of their tunnels, as such. Our explanation is that since they progressed almost in darkness, they had to make sounds, or in a narrow tunnel just to hum with closed mouth (on a sound like *mm* or *hm*), using the sound as a kind of sonar: the response of the cave or of the tunnel to this signal might tell whether there is space ahead and where to to progress. Reaching the location of maximum resonance (the acoustical main antinode) is very impressive: the whole tunnel resonates to a simple *hm* and the sound can be heard outside the tunnel, in the main cave (there are often pictures in front of the entrance of the tunnel). Progressing further inside the tunnel, one naturally finds oneself pausing at this remarkable sound location. And the dot shows precisely where this living sound point lies, possibly identifying it for use later on. This is our first prehistoric evidence.

Small decorated niches and recesses in Palaeolithic caves

But if the evidence of the red dots proves Palaeolithic people's awareness of resonance, one should expect there to be some more evidence of this. And indeed such dots or marks are also found inside or in the immediate neighbourhood of niches or small recesses. These recesses are too small to have a distinct point of maximal resonance; actually, the whole recess may resonate. As a general rule, *niches or recesses that are painted (with red dots, some marks or pictures) resonate strongly*. This rule applies also to niches, in the immediate vicinity or just in front of which such decorations are found.

Of course one should not expect all sounding niches to be decorated: there are usually too many niches in the cave. But it is interesting to observe that some of the decorated niches sound so easily and so strongly, even just with a single breath or a tiny sound, that it is inconceivable that the person who decorated the niche could have remained unaware of this phenomenon. It is what we call a *Camarin* effect (Reznikoff 2002, 44).

Decorating them entails making them resonate. There are such niches or recesses in several caves; moreover some possess exceptional decoration.

Probability is unnecessary here to establish awareness of resonance. Clearly those who marked them necessarily experienced a strongly resonance. To summarize our two first arguments, we may say that since Palaeolithic times the sounding quality of tunnels, recesses or niches was known and often used as such. And the same goes for the cave as a whole or for parts of it.

In fact, niches, recesses or alcoves were used as natural *resonators*. They prefigure and introduce our next piece of evidence: the deliberate introduction of small artificial niches, namely vases, into architectural constructions, in order to improve their sound quality.

Acoustic vases in theatres and churches

The principal reference to the use of acoustic vases, or *echea*, in Classical times is to be found in the *De Architectura* of Vitruvius. The vessels used were made of bronze or *terracotta*, earthenware, and according to Vitruvius *De Architectura* (I, 1, 9 and V, 4), were set out in niches around the seating-tiers of some theatres. They were tuned in unison or at the fifth and / or fourth of a main tone, within a range of one or two octaves, in order to amplify the sound of the voice (i.e. the singing voice as in the prosody or poetry of Antiquity). As far as I know, no such pots have been found in what are now the ruins of ancient theatres (see however Bruel 1951), but there is no reason to disbelieve Vitruvius; he is very precise and clear in his account. On the other hand acoustic earthenware pots are found and very well known in later churches. In some extant churches there are still more than a hundred pots in situ and there were more in some churches which no longer survive (for example 150 in the ancient church of Orval, in Belgium). Such pots are found throughout Christian antiquity. They are recorded, for example in the fourth-century church of St Victor in Marseille; they are very frequent in Romanesque and Gothic architecture and were still used in Baroque churches. They are found throughout the whole of Europe, including churches of the Russian and Byzantine tradition. Curiously, there are even two acoustic vases situated in the upper corners opposite to the stage of the Rachmaninov hall in the Conservatoire of Moscow (end of the nineteenth century).

The fact that the pots appear in Christian contexts both West and East indicates that their origin goes

back to Classical Antiquity; and this should not be surprising since we know that the works of Vitruvius were known and taught in the learned spiritual tradition transmitted by monasteries and monastic schools since Antiquity. There is no known use of pots in Roman temples, and it may be that there was no special interest in sound and resonance in temples in Antiquity (although for the use of the *absida*, see below). In the 4th century Christian tradition adopted, under the Emperor Constantine the Great, the Pantheon of Rome with its famous dome, built in the second century AD, as its prototype for the design of churches: firstly in Jerusalem's Holy Sepulchre and then at St Sophia of Constantinople, in the fourth century (reconstructed in the sixth). With the advent at the Pantheon of the semi-spherical dome, curves were now introduced into religious architecture: not just domes, but also vaults. Just as in the curved spaces of theatres, and because of the priority given to the voice in singing the Holy Scriptures, good acoustics were looked for; and sounding devices, such as pots, were used from time to time.

There is no mention in Christian literature, as far as I know, of acoustic pots in churches until the late Middle Ages, around the fifteenth century.[12] But of course we need to remember that there is virtually no literature about architecture or the construction of churches during the same period; so if we were to go simply by the evidence of literature we might have to conclude that there were no churches built at all! However, whenever pots are mentioned in later sources, it is always in relation to acoustics and *singing*. As Mersenne comments, in the seventeenth century, the pots are set 'in the arches or vaults of churches to help the voices of those who sing'. He explains that the pots are intended to *keep* and *reinforce* the sound (Mersenne 1636, 35).

Strangely, some modern studies of these vases have denied their usefulness from the acoustic point of view, but it must first be understood that their subjects were isolated vases examined in laboratory conditions and not sets of vases analysed *in situ*, in the resonant milieu of the church; moreover, they explored separated frequencies, for example of a speaking voice, and not of continuous singing tones. When one has such a voice and a trained ear, although one or two isolated vases in a church may not change the sound very much at all, the result with a full set of pots is very significant. The sound quality is greatly improved, through a process of reinforcement and *smoothing*, especially around the main frequencies of the vases — usually within the pitch-range of the male voice (100–400 Hz). Indeed in some resonances there are discontinuities in the resonant response: some tones (pitches) sound well, offering a good response, and yet suddenly some tones almost disappear: the resonance, in other words, is heterogeneous. To take an actual example, in the exceptional resonance of the church of the abbey of Thoronet (Provence) all the sounds — across a wide range of the human voice - elicit an equally good and indeed remarkable response, including lower tones. While in the church of the abbey of Sylvacane (also in Provence), as in many other churches, responses to some tones are weaker than others, especially at lower frequencies. There are, as far as I know, no pots in Sylvacane. Perhaps the resonance there proved good enough without them. These properties of sets of pots, reinforcing and equalizing or smoothing the resonance, have been confirmed by acoustical studies (Floriot 1978; Fontaine 1981).

In most cases pots are distributed in the vaults; but they are also sometimes found in the walls of the choir, at different heights. In the church of Thoronet there are some small cavities at the top of the vault. No pots are contained in them. Nevertheless they appear to have no other architectural rationale: perhaps they were put there to receive pots in the event that the church did not sound as expected; but it does, as we have seen, extremely well.

That there is some acoustic intention behind these devices has never been questioned; for trained musicians, they do have a distinct acoustic effect, and are therefore clear evidence of conscious use and appreciation of sound resonance in churches. In summary, such interest in resonance and its various musical qualities has evidently persisted since ancient times, from Vitruvius to Mersenne and beyond, and is attested both in the ancient literature and from archaeological observation, corresponding to points (a) and (c) above.

The round shapes of these pots and their frequent association with vaults, introduces us to the employment of cylindrical and spherical surfaces in overall architectural construction as further ways of improving sound qualities of buildings.

The apse

One of the main characteristics of churches in Christian antiquity is the vaulted apse (from the Greek *absis*: circle, vault; *absida* in Latin). This can be related to the general use of curved surfaces in architecture. In the fourth century AD, when Christian culture and art emerge and become open to the learned and spiritual knowledge of Antiquity, the masters of architecture and the arts are of course the Romans. From Gaul to North Africa and the Near East they built palaces, theatres, arenas, bridges, aqueducts, bath-complexes

(*thermae*) and temples. They mastered the technique of vaulting, particularly for thermae. But the first *religious* monument where the technique was exploited was, as we have seen, the Pantheon of Rome with its famous dome. Built in the second century BC and then rebuilt in the second century AD, it has for more than 1800 years remained structurally perfect, not a stone has moved. Probably because of its name, but also certainly for the beauty and ideal of a dome representing the sky's vault, Constantine the Great (died AD 337) adopted the Pantheon as his architectural model for the further development of the Christian church. Since then, domes and vaults have been used in Western, Byzantine and Russian traditions, and, transmitted by Byzantine architects, were adopted for the Muslim mosque. Subsequently their use spread all over the world. The same techniques of vaulting necessary for domes and half-domes were used for apses and vaulted naves.

One of the advantages of a vaulted ceiling, properly constructed, is that, since it does not use wood, it can last for ever, as we can see from the dome of the Pantheon or the much larger dome of St Sophia of Constantinople (sixth century AD). The vault of the abbey church at Thoronet, completed in AD 1200, also remains perfect to this day, as do the vaults of so many other churches and cathedrals. The second advantage of vaults derives from the quality of the resonance they induce. Resonance is reinforced and improved by curved surfaces. According to the elementary laws of propagation and reflection of sound, cylindrical and spherical surfaces not only concentrate and focus sound but also enhance and prolong the harmonics (overtones) of the original sound.

So, despite the great technical difficulties involved in erecting a vault, its advantages are obvious; however, because there are other architectural advantages as well it is not possible to argue that acoustics were the only consideration in erecting vaults.

The apse is quite a different matter. The apse has the shape of a half-dome (or semi-cupola); sometimes even of two separate half-domes, one placed above the other. There is absolutely no architectural reason for such a complicated construction, when a simple flat wall would be perfectly adequate, exactly as it is at the entrance of the church, at its west end. The reason for the complex curved shape of the apse seems obviously acoustic: it focuses the sound of the singing voice facing the apse where the altar is located (from the earliest times, the celebration was sung by the priest). From there the voice can be heard very distinctly up to 100 m away. Because of the apse's shape and of the vaults above, the whole church may resound quite extraordinarily, even with a single voice singing, particularly in natural intervals; the resonance and the richness of the harmonics often give the impression of a singing choir, the choir of angels mentioned above, following the ancient Christian tradition.[13]

This is the most remarkable evidence of the practical knowledge and use of sound resonance. It certainly represents the highest acoustic achievement in architecture, especially in the Romanesque churches of the eleventh and twelfth centuries. As a work of acoustical engineering, the church of the abbey of Thoronet is a wonder of the world.[14]

Curiously enough, the acoustical rationale behind the complex shapes of apses is never explained in architectural studies or descriptions of churches. In our modern cloth-eared age it is rather suggested that the acoustical properties we hear 'decorate' the architecture, its vaults and arches, whereas it is of course quite the other way around: the architecture was conceived to serve the praise of the Divine World and therefore of the sound. The singing voice of the celebrant must be heard and the beauty of the chant must be enhanced by an appropriate treatment of the building: by an apse and a vaulted nave.

Historically speaking, the origin of the medieval apse is to be found (1) in the absida of the Roman temple, where it is semi-circular but with a flat ceiling; and (2) in the niches constructed in walls to house statuary. Such niches, with the statue removed, became what were called *martyria*: niches with hemispherical ceilings, erected for family worship of the dead and ancestors (Grabar 1943–46). Here again the curved shape focuses the sound and reinforces some higher overtones. This quality was to be mastered with the erection of apses in churches from the fourth century onwards.

Sometimes an adverse acoustic consequence of a dome is that it can concentrate sound under its own volume; a well-proportioned apse, on the other hand, may correct or at least offset this flaw, when the celebration of the Divine Offices is performed at the altar and the celebrant is facing the apse.

In the Western tradition, perhaps for this very reason, large domes are used much less frequently than in Byzantine and Russian traditions. It seems that it is clearness of sound and a relative openness which characterize Western church architecture, contrary to the late Orthodox tradition, where an iconostasis separates the apse and the altar from the transept and the nave, destroying the resonance.

It is very interesting that St Bernard (died AD 1153) decided, for the sake of the simplicity he wanted for the Cistercian order, that the wall at the altar side should be flat, without any apse. This of course was simpler to achieve, from the architectural point of

view, but not necessarily beneficial from the acoustic one. There was opposition from within the Order; and when he died, apses began to reappear, despite the difficulty involved in erecting them. The abbey church of Thoronet, which belonged to the Cistercians, however, has a magnificent, deeply curved apse and no fewer than four apsidal chapels. The many churches that adopted the flat end-wall , for example the abbey churches of Sylvacane (Provence) and Fontenay (Burgundy), do not sound the same as those with apses; when one sings from the choirthere is an obvious scattering of the sound, quite contrary to the focusing which an apse achieves. The sound is less clear, less powerful, although it may still be very beautiful because of the vaulted ceiling of the choir and the nave.[15]

Conclusion

We can see, through the ages, continuity in the discovery and use of resonance and of its marvels: naturally vaulted galleries, curved recesses and round niches, or artificially made pots and apses or vaulted choirs and naves. From the Palaeolithic caves to antique theatres and churches with the same curved lines and forms, resonance was appreciated for celebrations, chanting and singing, with the human voice praising the Invisible and its resonating mysterious sounds. In fact these curved lines are also those of our skull, palate and throat which have in a very real sense an apsidal structure, serving a similar projectory function.

It is remarkable that alongside these architectural and acoustical adaptations, which are common to caves, temples and churches, there is one other common element: pillars, whether made from the junction of stalactites and stalagmites, forming fluted columns,[16] or man-made pillars of ancient Greek and Roman palaces, theatres and temples, and of course medieval churches. It is as if the same cave, the same sanctuary, the same cathedral was rediscovered or reconstructed ever since our first and deepest sanctuary: in the womb of our Mother — woman, earth or God (Reznikoff 2005). Nowadays this understanding and practice of architectural sound is lost; or rather, as I pointed out in the introduction, it is concerned with quite different needs: because, of course, resonance must be avoided for modern orchestras, ensembles and their music. Opera and concert halls today are thus built according to a completely different acoustic premise. The magic practice singing with echoes is forgotten.

Moreover, even when performances take place in a temple or sanctuary, it doesn't mean that the performers always use and appreciate its ancient resonance. Today, almost all of the concerts performed in Romanesque churches ignore or even, by means of stages, curtains and other devices, try to avoid the often remarkable acoustics of these churches. But here we meet a genuine difficulty: to really sing *in a resonance*, that is, fully using its acoustic character, we need to sing in *just intonation* i.e. in the natural pure intervals of resonance, and not those of the modern equally-tempered scale. Just intonation was, of course, precisely one of those natural tonalities which characterised ancient singing. These intervals are still, although decreasingly, practised in the musical traditions which have preserved the spirit of Antiquity by oral transmission of their learned spiritual chant and music. For many of us, a rigorous practice of natural intervals in strong resonances has been a wonderful school for just intonation and an entry-point into ancient modal chants. This opens onto a wide world that extends, as we have seen, from the depths of caves and the rituals of ancient temples and churches to choirs of angels sounding in everlasting divine harmony.

Notes

1. See also Reznikoff 2002, and for a study around lakes, in Finland, Reznikoff 1995. See also Goldhahn 2002.
2. See the author's studies on the resonance of Romanesque and Romanesque-Gothic churches in the booklets of the CDs quoted in the footnotes below.
3. In the marvellous resonance of the church of Vézelay (Burgundy, France), I used, for early Christian chant performed in natural intervals, the most resonant (Romanesque) part of the basilica, while M. Rostropovitch, for his recording of the Bach's Suites for cello solo, used the less resonant (Gothic) part of it. Listen to *Le Chant de Vézelay* (Le Vase de Parfum), Studio SM, (1221.16), Paris, 1992, and *Le Chant de Vézelay* (Marie-Madeleine au Tombeau), Studio SM, (1221.62), Paris, 1993, and M. Rostropovitch, *J.S. Bach, Suites pour violoncelle*, 2 CD, Emi classics (5554922), 1995 (recorded 1991); also in DVD (5991599).
4. My record-breaking performance, with, by chance, ideal conditions on the lake of Valamo in Finland, scores at twelve echoes. It was real magic.
5. For Verulam, see Lot 1939, 97; and for Mold, see Usher 1639, ch. XI. At Mold there is still a Maes-Germen Valley. These two references are taken from de Lyon 1965, 86–7.
6. Cf. *Le Chant du Thoronet* (CD), Studio SM, Paris 1980, where this Alleluia is performed.
7. A. Prudentius, *Peristephanon*, Hymnus V (St Vincent's Passion), v.313–16.
8. St Vincent is therefore the patron saint of those who sing in a resonance and particularly the patron saint of the musical archaeologists working on the resonance of monuments and, of course, of caves.

9. At Arcy the correlation is straightforward: the more the echoes in the cave (up to seven) the more the pictures.
10. See Reznikoff 202b, 42 & 46 (for caves), 50 (for rocks in open spaces where the criterion is based on the number and quality of echoes). The criterion of echoes given by clapping hands as suggested by S. Waller is, in many cases, certainly too poor or too loose a criterion for reliable results; a voice, making sounds in natural intervals is usually the most relevant, it is, of course, anthropologically the richest and most valid tool to study and understand a possible human awareness and use of resonance in caves for rock sites (**see below??**).
11. As we discovered it in Le Portel.
12. See Viollet-Le-Duc 1895, 471–2; Viollet-Le-Duc was probably the first to study acoustic vases, he quotes a text of the year 1432. The pots are mentioned later by Italian Renaissance architects e.g. Francesco di Giorgio Martini (1490). An early modern study is Hills (1881–82, 65–81). This reference is quoted from Tallon (1992); A. Tallon was my former student. The recent studies are Floriot (1978), his important *Contribution à l'étude des vases acoustiques du Moyen-Age* (1964), and Fontaine (1979; 1981).
13. Cf. *Le chant de Vézelay* (see footnote 3).
14. Cf. *Le Chant du Thoronet* (see footnote 6).
15. Cf. *Le Chant de Fontenay* (CD), Studio SM, (1216.40) Paris, 1989.
16. As in Oxocelhaya (Pays-Basque).

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