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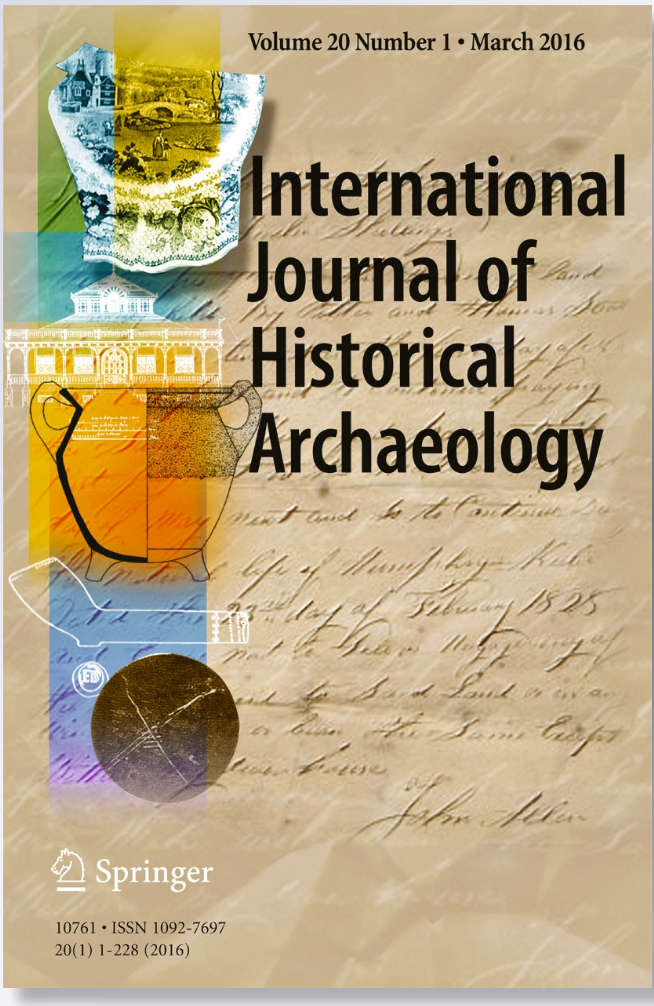
International Journal of Historical Archaeology

ISSN 1092-7697
Volume 20
Number 1

Int J Histor Archaeol (2016) 20:127-145
DOI 10.1007/s10761-015-0325-2



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Revisiting Historic Buildings through the Senses Visualising Aural and Obscured Aspects of San Vitale, Ravenna

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Published online: 31 October 2015

Abstract Applying new information technologies to Cultural Heritage enables us to discover the unexplored characteristics of visual and aural attributes of historic buildings. In this article a new technology to measure acoustic 3D Impulse Responses in historic interiors is described and applied to the sixth-century church of San Vitale at Ravenna, Italy. The virtual reconstruction of this important UNESCO World Heritage Site revealed otherwise obscured yet intentional details of its architectural design. The results of measuring the internal spatial parameters are used to recreate San Vitale's historical components and to re-sound original music of the little known Ravennate rite.

Keywords Archaeoacoustics · 3D Auralization · 3D Visual and audio reconstruction · Multichannel IRs measurements · San Vitale, Ravenna · Historical reconstruction

Introduction and Research Aims

The design, survey and construction phases of an ancient interior and its use over time are of interest to archaeologists and architects. The virtual realisation of an ancient interior space can make visible non-visual sensory impressions such as sound atmospheres and reveal obscured material relationships, enriching our understanding of past aspects of cultural heritage. These non-visual atmospheres and hidden relationships can be recreated by means of virtual and augmented reality, but the video and audio quality is not considered of fine enough definition (Vlahakis et al. 2001). The recent development of acoustic methodologies in achieving the spatial sound distribution in enclosed

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interiors has greatly enhanced the possibilities of recreating past sound atmospheres. When new developments in visual virtual reconstructions of rooms accompany thorough descriptions of the 3D acoustic environment, a fully integrated sensory experience of virtual reality is achieved and can better assist in our understanding of past experience. The sixth-century basilica of San Vitale in Ravenna, Italy (Deichmann 1989) is chosen as a case study to experimentally rectify this problem. The aim of this paper is to highlight the results of aural and visual methodologies employed at San Vitale to reveal important hidden and unseen elements of its meaningful atmosphere.

A multidisciplinary research campaign incorporated acoustical and archaeological methodologies. Innovations were employed to enhance measurements of spatial sound distribution and a virtual reconstruction of the acoustic characteristics of San Vitale (Tronchin and Knight 2008; Tronchin et al. 2007). The acoustical survey of 3D Impulse Responses was recorded between the range 20 and 20000Hz and from these were calculated acoustical characteristics including Reverberation Time (RT20 and RT30) along with speech and music reception Clarity (C50 and C80). The results of a campaign to measure the internal spatial parameters of San Vitale, employing the new methodology, are utilised to recreate historical components of the church and to re-sound original music of the Ravennate rite. A new vocal rendition of the Ravennate chant *Lux de luce Deus tenebris illuxit Averni* (Levy 1971) was recorded on the ground floor and in the upper *matroneum* gallery. A further vocal performance was recorded in a 90Hz anechoic chamber at the Institute of Sound and Vibration Research (ISVR) at the University of Southampton, and convolved with the surveyed Impulse Responses of the church.

The church's design, survey and construction phases were scrutinised by using virtual modelling (Durvilli 2009; Giannakopoulou 2007) and converting metric measurements (Deichmann 1989) to original Roman units (Knight 2010). Otherwise obscured, yet intentional, symmetries and design features of San Vitale were newly identified along with significant direct correlations and congruent relationships with the older octagonal Arian baptistery at Ravenna. Visibility analysis included natural illumination experiments and the reconstruction of an original sixth-century San Vitale window. The results of this research campaign are presented here with a re-evaluation of San Vitale's contextual meaning within sixth-century Mediterranean architectural and social history.

During the past two decades, as digital technologies have become increasingly sophisticated in acquiring real data and modelling faithful reconstructions, improvements have suggested interesting applications in the valorisation of historical, cultural and artistic heritage. In particular, the possibility of digitally acquiring and restoring reality-based models of artefacts allows us to improve digital archives and catalogues by organising and managing information using 3D models as intuitive graphic interfaces. By restoring the intrinsic 3D characteristics of artefacts, reality-based models facilitate communication and also provide accurate and detailed information about the shape, chromatic and radiometric appearance of what is represented. Moreover, the digital acquisition of models preserves 3D information that would otherwise change over time. These data can therefore be considered as references during preservation or restoration interventions. The 3D models also allow us to build virtual reconstructions of sites that have changed, providing accessible online digital archives to scholars in different locations and times to access and share information. This possibility encourages data cross-analysis among various research teams and invites interesting applications in different disciplines, including archaeology, architectural history, musicology, illumination studies and acoustical science. As a consequence, recent developments of digital technologies and methodologies coupled with the possibility of creating and managing digital replica of artefacts, allows curators to enrich exhibitions with virtual reconstructions of complex sites, as well as displaying and sharing objects in digital environments that are owned and managed by institutions at a physical distance from one another. In addition to these advantages, producing physical replica of material remains using digital technologies (e.g., rapid prototyping) provides a significant improvement to physical reconstructions of archaeological sites. For example, the development of these technologies and procedures enables us to collect together replicas of original objects that are inaccessible either because they no longer exist or because they are situated at different geographical locations.

Methods

Many attempts have been made to standardise the acoustic measurement of theatre and sacred interiors (Martellotta et al. 2009; Pompoli and Prodi 2000) by taking into account room conditions and employing multiple sound source and microphone positions. However, only a few attempts have been made to describe and standardise the test signal, the type and variety of sound source and the microphones employed during the measurements (Farina and Tronchin 2005, 2013). These specifications become crucially important when the Impulse Responses (IRs) are required to perform 3D auralization of a room rather than simply obtain the numerical values of ISO 3382 parameters, i.e., the International Standard Organisation 3382 standard, 2009.

Recently, a substantially more powerful, elegant and simple measurement system has been proposed (Farina and Tronchin 2013), based on a spherical microphone array equipped with 32 capsules mounted on the surface of a small sphere (80 mm diameter) which contains the preamplifiers, the A/D converters and an audio-over-ethernet chipset called the Eigenmike™. This probe makes it possible to measure 3D multichannel Impulse Responses and provides a much finer spatial resolution not possible even one year ago. Despite several technologies and methodologies for 3D digitisation have been developed and improved, the lack of a standard procedure, along with associated restrictive costs, continue to discourage the systematic and comprehensive digital acquisition of historical collections and heritage.

Previous quantification of the visual characteristics of a room did not fully measure how difference surfaces reflect or refract light, nor how window glass transparency values affect light transmission and intensity, all essential factors in accurately reconstructing the visual characteristics of an interior space. Moreover, the photometric characteristics of light sources ought to be considered where the virtual augmented reality includes the combination of natural external lighting and artificial internal lighting schemes. Aided by present capabilities, these new acoustic and visual methodologies are applied to an extremely complex and detailed architectural example – the sixth-century basilica of San Vitale at Ravenna, Italy.

The Basilica of San Vitale, Ravenna

San Vitale has been chosen for this study because it meets essential criteria: it is one of the earliest survivals in the West in which we can also be reasonably certain of its architectural function and usage as a congregational church, its interior space is well preserved and we are confident that vocal chant has been performed within the interior since its dedication in 548 CE. The state of preservation and continuity of function in this important UNESCO World Heritage Site allows for the innovative technological investigation conducted and reported here. Further, archaeological methodologies are employed to contextualise the meanings of the data results and discoveries which are new contributions to our understanding of sixth-century Ravenna.

In 526 CE Ecclesius, bishop of Ravenna, initiated an ambitious building programme within the western imperial capital, under Ostrogothic rule, of three congregational churches. San Michele *ad Frigiselo* (now "in Africisco") is a traditional longitudinal basilica. Santa Maria Maggiore may have originally been designed as a small free-standing dodecagon but soon afterwards developed as a longitudinal basilica by the addition of an abutting nave (Deliyannis 2010, p. 222). San Vitale is larger in scale than these two churches, designed as a centrally planned octagonal two-storey congregational church, possibly originally intended as a *martyrium* for local bishops (Deliyannis 2004, p. 177). It is both externally and internally octagonal, with eight internal piers supporting a drum and dome.

San Vitale is situated immediately west of Santa Maria Maggiore and the mid-fifth-century Santa Croce, upon Ecclesius' legal property (*proprietatis iura*) in the north-west region of Ravenna, probably an area dedicated to the Apostles (*regionem apostolorum*) (Deliyannis 2004, p. 128). The addition of Santa Maria Maggiore and San Vitale to this small parcel of land creates a meaningful sequence of Christological encounters of the Nativity to Crucifixion and concluding with San Vitale signifying the New Jerusalem (Knight 2014). The site was formerly a cemetery in which a small late fifth-century funerary *sacellum* stood. San Vitale was built to incorporate this *sacellum* and eventually, under Bishop Maximianus, dedicated on April 19, 548 (Baker 1993, p. 186). This was Low Sunday, otherwise known as the Octave of Easter or *Quasimodo* Sunday - the first Sunday after Easter (in the Julian calendar Easter Sunday was April 12, in 548). This relates to other contemporary Ravenna church dedication dates - San Michele in Africisco was dedicated on May 7, 545, the third Sunday after Easter (Easter Sunday was April 16 in 545) (Deliyannis 2004, pp. 184–185, 308) and Sant' Apollinare near Classe was dedicated on May 17, 549, the fifth Sunday after Easter (Deliyannis 2004, p. 192), also known as Rogation Sunday.

Designing San Vitale

Significant features of San Vitale's design stage are only properly revealed when the original measurement units are considered (Campbell 2000, p. 482). The conversion from metric measurements (Deichmann 1989) into original sixth-century units reveals a number of interesting congruent architectonic relationships within the church and also beyond to its wider urban context. One particular direct correlation is demonstrated (Fig. 1); the two small octagons of San Vitale - the inner octagon enclosed by the billowing *exedrae* and the polygonal exterior of the apse, experimentally projected as a

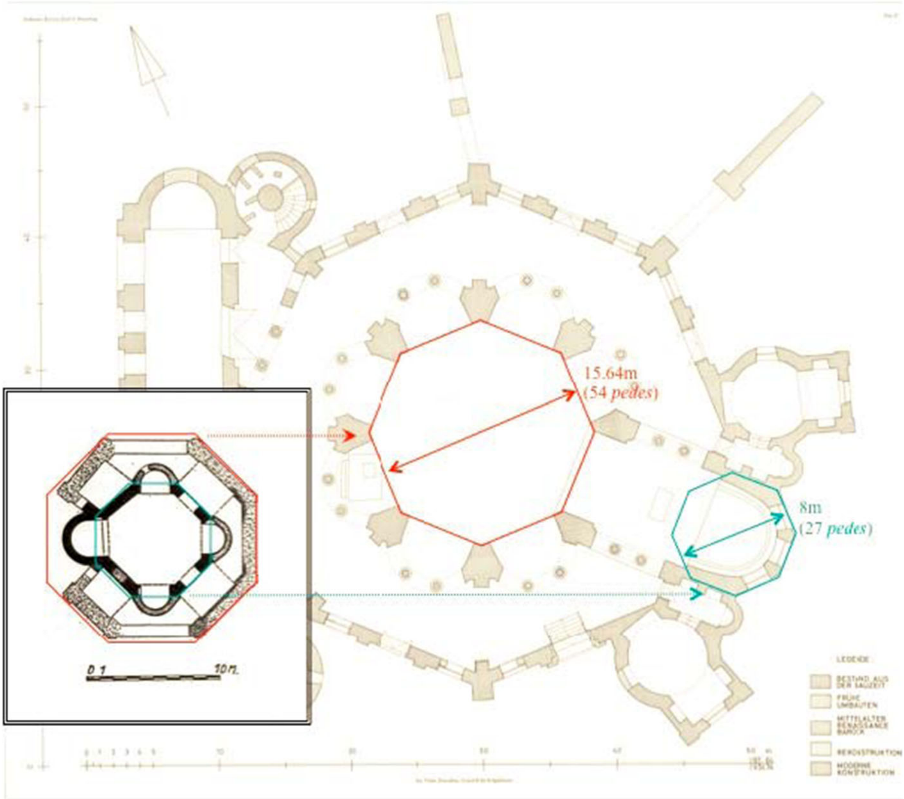

Fig. 1 Congruent octagons of the Arian baptistery and San Vitale (after Campbell 2000, p. 52; Deichmann 1989, Plan 27)

complete octagon - are each equivalent in measurement to the octagons employed in the earlier (ca. 500–525 CE) octagonal Arian baptistery also at Ravenna.

The Arian baptistery's smaller octagon and San Vitale's polygonal apse exterior are both 8m wide, converting closely to 27 Roman feet, or *pedes* (16.1 mm short of 27 *pedes*). Similarly, the external octagon of the baptistery and San Vitale's inner octagonal space are both 15.64 m wide (Deliyannis 2010, p. 180; Verzone 1967, p. 52), which is almost exactly 52.5 *pedes*+1 *palmus*+1 *uncia* (1.34 mm short of 15.64 m). The relation of the smaller octagon to the larger has a ratio close to 2:1 (27 *pedes*×2= 54 *pedes*). The baptistery's smaller octagon is contained within the larger, whereas in San Vitale the relationship has undergone a Euclidian metric transformation by translation - the smaller has been shifted laterally away from the larger. While San Vitale's inner octagon, contained within the larger external octagon (119 *pedes*), echoes the baptistery's layout the original ratio is lost (as 54 *pedes*×2=108 *pedes*, not 119 *pedes*). These measurement equivalencies are not shared with the older Orthodox baptistery at Ravenna, which dates to ca. 458 CE (Lowden 1997).

The statement that the octagonal baptistery adjoining the sixth-century longitudinal basilica at nearby Ca'Bianca has "the same layout and dimensions as the Arian Baptistery" (Deliyannis 2010, p. 198) requires clarification. The only close comparison between the two baptisteries, other than their shared centralised octagonal form, is that the internal width of the inner octagon at Ca'Bianca is approximately 8 m (Deliyannis 2010, Fig. 69), as is the external width of the Arian baptistery's inner octagon. However, the external width of the outer octagon at Ca'Bianca is approximately 18.5 m, almost 3 m larger than the Arian baptistery. Therefore aside from an overall likeness and some correlation between the Arian baptistery and the baptistery at Ca'Bianca, the commensurate relation between the former and San Vitale remains a significant identification.

San Vitale also copies a rare design feature of the Arian baptistery. Unlike other known centrally planned late antique baptisteries, the circulating ambulatory of the Arian baptistery terminates either side of the apse. Likewise, San Vitale's ambulatory is interrupted by the chancel which springs from the inner octagon. The innovation of an interrupted ambulatory appears to be a local Ravennate feature shared by these two structures. The measurement conversion also revealed meaningful aspects of the original survey phase of San Vitale.

San Vitale's Sixth-Century Survey

By converting the metric plans of San Vitale (Deichmann 1989) to original Roman measurements it is observed that the main exterior octagon of San Vitale was created by superimposing two *actus quadratae* (Fig. 2), the second rotated 22.5°.

The *actus quadratus* was a standard Roman land measurement, 120 *pedes* square equalling one acre (Campbell 2000, p. 482). The use of this measurement as the basis for San Vitale's main octagon demonstrates that an important Roman land measurement remained part of the vocabulary of urban planning into the middle of the sixth-century.

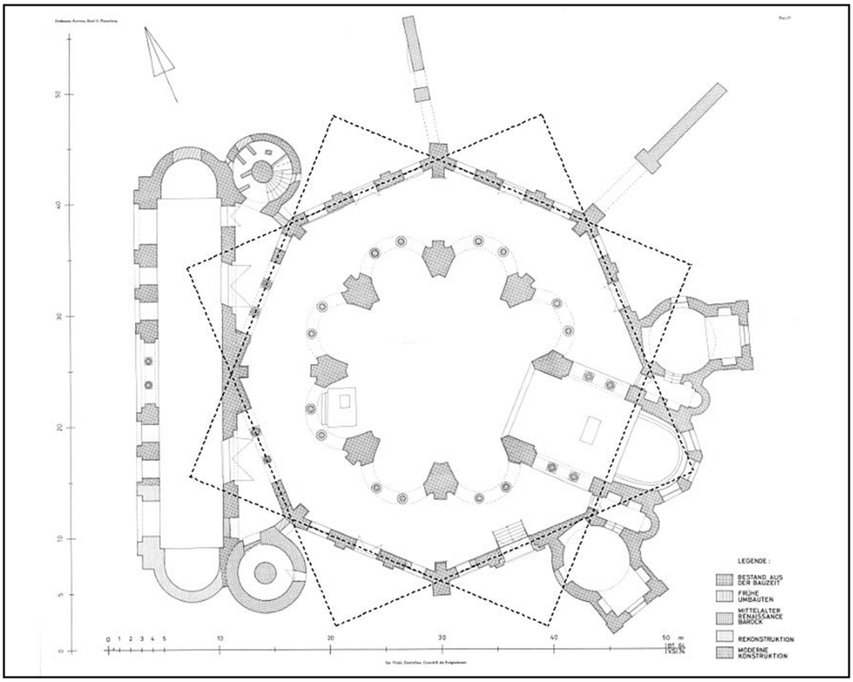

Fig. 2 Two superimposed *actus quadratae* creating the main exterior octagon of San Vitale [after Deliyannis 2010, Plan 27]

San Vitale's apse does not align with the east as in the majority of late antique congregational churches (Krautheimer 1986, p. 1965). The logic of this apparently skewed orientation is only revealed when the church is understood within its urban topographic and historical context. The exact positioning of the *actus quadratae* that create San Vitale's external octagon is dictated by the position and orientation of the older late fifth-century funerary *sacellum* now inside the church. San Vitale's alignment is rotated exactly 22.5° from this rectangular feature, perhaps originally the location of a small altar but now a water filled pool known as the "Well of St Vitalis." By respecting and incorporating the orientation of the *sacellum*, San Vitale is effectively rotated away from the street grid by 17° but its apse alignment is observed to project directly to the centre of the entrance narthex of San Michele in Africisco. The orientation of San Vitale illustrates how Ecclesius' building program, of which these two churches were part, significantly and meaningfully altered the sacred urban topography of the western capital.

Constructing San Vitale

Several repeated measurements are identified in the architectural design of San Vitale. The interior length of the chancel and apse is 55.31 *pedes* (16.354 m) and the height of the seven *exedrae* is 55.36 *pedes* (16.376 m), a mere 22 cm difference. Likewise, the width of the floor between the *synthronon* stone seating benches at the interior of the apse and the width of the seven *exedrae* are all 18 *pedes* (5.2 m). Therefore, the chancel and apse effectively combine as an eighth *exedra* that has been laid down in plan. Due to viewer perspective this equivalency is not necessarily noticeable and represents an artefact of the specialist knowledge of the architect, as Agnellus has it, the *archiergatus* or *princeps operis* (Deliyannis 2004, p. 312, note 17).

An obscured aspect of San Vitale's internal design was newly identified, only revealed during the process of creating a virtual model. The spatial distribution of column base shapes was identified as displaying an intentional harmonious logic (Knight 2010, p. 88–90). The seven pairs of Proconnesian marble columns between the central piers of the internal octagon have octagonal bases resting on circular plinths. The two pairs of columns either side of the chancel have circular bases resting on square plinths. This arrangement is reversed on the second story *matroneum*. The seven pairs of columns between the central piers of the internal octagon have circular bases resting on square plinths and the two pairs of columns either side of the chancel have octagonal bases resting on circular plinths. This vertical spatial patterning is not easily perceptible by the senses alone. For example, members of the congregation on the ground floor could not observe the column base shapes above them in the *matroneum*. Even from the elevated vantage from the *matroneum* this internal logic is difficult to observe. Since this inconspicuous spatially distributed logic was only observed while creating a virtual model, it has been posited that a 3-dimensional scaled architectural model may have been created prior to construction (Knight 2010, p. 247). Further, the apse mosaic depiction of Bishop Ecclesius carrying a scaled model of San Vitale may represent an actual maquette used for the purposes of demonstrating the design and phases of construction (Knight 2010, p. 227, 247–249).

Together, the commensurate measurements and distributed spatial design features of San Vitale demonstrate intentionality in the design, survey and construction phases of the church. These various concealed details may not necessarily have been known to the wider community of sixth-century Nicene Orthodox congregants but they do reveal the intentionally extensive cohesiveness of the design and survey stages of the church. Beyond Bishop Ecclesius and his successors during the construction phases of San Vitale, and perhaps select members of the royal court, it is even doubtful whether these abstruse obscurities were known to the extended clergy. Nevertheless, they combine to support the intrinsic identity of this church as a unified whole. Having revealed some of the most striking elements of San Vitale's design, survey and construction phases, the innovative experimental results of measuring and simulating the acoustic character and natural illumination of the internal space is discussed next, in order to reveal the aspects of the sensory affecting impact this church may have had on the sixth-century congregation.

Enhanced Acoustic 3D Measurements in San Vitale

To acquire enhanced acoustic 3D measurements in San Vitale, the excitation-deconvolution technique was employed. By following a recently developed technique (Farina and Tronchin 2013) it is possible to capture the entire 3D acoustic propagation of sound in a room. Moreover, by means of a properly designed listening room, the sound can be reproduced by means of enhanced 3D auralization methods based on Ambisonics and Stereo Dipole (Tronchin et al. 2005). For the measurement of the Impulse Response, a special excitation signal was used, known as the Exponential Sine Sweep method (ESS) (Farina 2000). The advantage of employing this method is that it is possible to calculate the Impulse Response of the linear system while avoiding contamination due to distortions, which usually occur in the loudspeaker, and to obtain a large value of the signal-to-noise (S/N) ratio.

Sound Sources

The choice of sound source is important for measurement and the subsequent 3D auralization stage. The standard ISO 3382/2009 requires an omnidirectional sound source for measuring room Impulse Responses. Even though the omnidirectional loudspeaker does not correspond to the effective directivity pattern of real-world sound sources, it is preferable when the purpose of the measurements is to precisely determine the sound distribution in a room. It avoids exploiting room effects such as abnormal concentrations of energy and focalisations for selected orientations of the source as can happen when employing highly directive loudspeakers. A custom-built dodecahedron, incorporating a perfectly-flat digital equalisation system, was the preferred choice for measuring San Vitale's acoustic characteristics. Complimentary to this was a vocalised sound source, as singing a Ravennate chant is appropriate for the interior of San Vitale.

Ravennate Chant in San Vitale

Of six remaining Ravennate chants, *Lux de luce Deus tenebris illuxit Averni* (Levy 1971, p. 48) is identified as the most appropriate vocal sound source for San Vitale as it arguably dates to before 601 CE (Levy 1971, p. 54). The liturgical context of this versus is the Easter Vigil *lucernarium* (Levy 1971, pp. 52–54) when the Paschal candle was lit.

Mainstone (1988) has demonstrated that in the primary sources relating to Hagia Sophia the upper gallery (*matroneum* or *gynaikonitis*) was a designated area for women (Mainstone 1988, p. 230). The *matroneum* of San Vitale has been posited as a space utilised in a similar manner (Knight 2013; Paliou and Knight 2013). Part of the acoustical measurement of San Vitale included a vocal experiment - *Lux de luce* was sung in unison by a male vocalist (D. J. Knight) on the ground floor in the *exedra* south of the chancel and a female vocalist (Dr. Maddalena Roversi) at the north *exedra* in the *matroneum* gallery, opposite and visually accessible to each other. Listeners in the inner octagon of the church clearly heard both vocalists singing in unison and the Reverberation Time enhanced the immersive quality of the space and music.

A proper comprehension of the acoustic effects of San Vitale in relation to the performed *Lux de luce* was achieved when the process of auralization was completed. Auralization was performed by convolution, where the Impulse Responses are employed as very long Finite Impulse Response (FIR) filters, applied to dry (anechoic) recordings (Farina and Tronchin 2005, p. 4), convolution being a very efficient filtering technique to sample and simulate the acoustics of a real space to provide a realistic sensation of sound diffusion (Shimokura et al. 2011; Tronchin 2012; Tronchin and Coli 2015). A second male vocal performance of *Lux de luce* (by the author) was recorded in a 90Hz anechoic chamber at the Institute of Sound and Vibration Research (ISVR) at the University of Southampton. This was convolved with San Vitale's acoustic characteristics and the interior space of the church was subsequently experienced in the *Arlecchino* listening room at the laboratory of DIN – CIARM, University of Bologna (Farina and Tronchin 2005; Tronchin et al. 2007).

Advances in archaeological visualisation methodologies makes it feasible to overlap the mapped visual and acoustic data. Models have been created to study simulated movement into and through San Vitale's space and the effects of physiological encounters with specific sensorial realities of the world, namely combinations of the visible and acoustic (Knight 2013, 2014; Paliou and Knight 2013).

A New 3D Virtual Microphone System

The above-mentioned sound sources were recorded. The ISO 3382 (2009) standard usually requires omnidirectional, monaural microphones in measuring acoustic parameters and only specifies the dimension of these microphones (preferably less than 13 mm). Moreover, the ISO 3382 describes the characteristics of eventual binaural microphones (real or dummy heads) that can be used to measure binaural Impulse Responses and Inter-Aural Cross Correlation (IACC). This ISO standard also considers using figure-of-eight microphones to measure certain lateral-energy parameters, such as Lateral Efficiency (LE) and Lateral Fraction (LF).

Apart from the binaural measurements, a Soundfield microphone is the optimal transducer for performing 3D Impulse Response measurements; the W channel is good for the monaural parameters (omnidirectional) while the Y channel provides the figure-of-eight signal required for computation of LF. Two other directive channels (X and Z) can be used for recreating the entire 3D soundscape inside a playback environment making use of 1st-order Ambisonics technology (Farina and Tronchin 2005).

A new microphone system was recently developed in Italy for real-time recording/broadcasting applications, by the RAI Research Centre in Turin and Advanced

Industrial Design in Acoustics (AIDA), a spin-off company from the University of Parma (Farina and Tronchin 2013). It is based on a 32-capsule spherical microphone array (Eigenmike™) and real-time filtering software capable of synthesizing up to seven virtual microphones that can be moved in real-time and with variable directivity and zooming capabilities. The pattern is chosen among a family of cardioid microphones of various orders, according to this formula:

$$Q_n(\vartheta, \varphi) = [0.5 + 0.5 \times \cos(\vartheta) \times \cos(\varphi)]^n \quad (1)$$

Where Q_n is the directivity pattern, n is the directivity order of the microphone and ϑ, φ the vertical and horizontal angles (Fig. 3).

When this system is employed for 3D Impulse Response measurements, rather than synthesising only seven virtual microphones with variable aiming and directivity in real-time, a post-processing Matlab application is employed to create 32 virtual microphones with fixed directivity patterns (6th-order cardioids) and aiming - in the same directions as the 32 capsules located on the spherical surface. If the aiming directions of the 32 virtual microphones are plotted over a panoramic 360×180° image taken from the microphone positions, one can "see" where the 32 microphones are pointing (Fig. 4).

Post Processing

After all 32-channel Impulse Responses have been measured at each position it is possible to post-process the results in two ways. First, a graphical analysis can be performed to show the spatial distribution of the incoming energy along the running time, allowing us to "see" from where in the room the reflections are coming. Secondly, an audible rendering can be presented to a group of listeners inside a room specially equipped with a suitable array of loudspeakers completely surrounding the listening area within a sphere (i.e., Ambisonics). The Ambisonics method reproduces the 3D sound distribution in a room by using a truncated spherical harmonic decomposition of the sound field. This corresponds to the sound pressure W, and the three components of

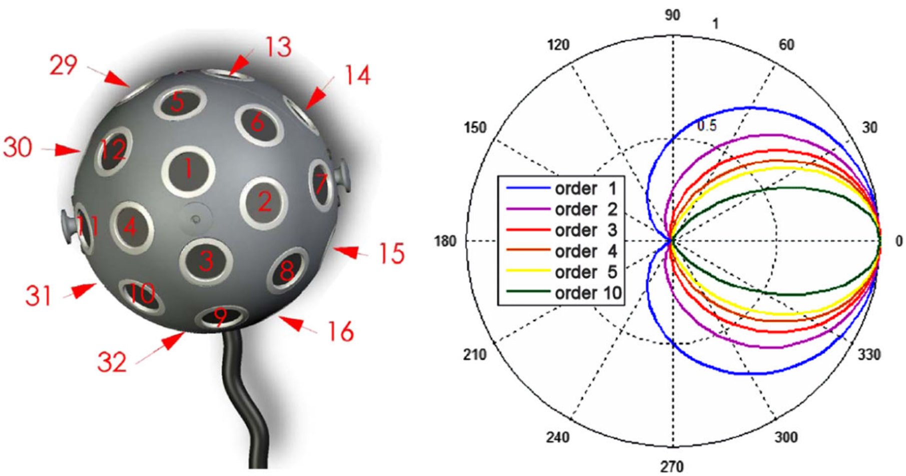

Fig. 3 Capsule positions and directivity patterns of the 3D virtual microphone

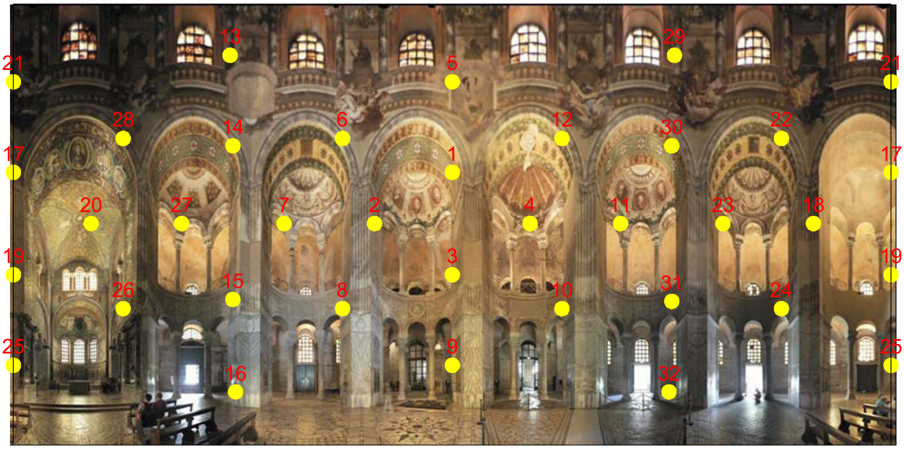

Fig. 4 The 32 virtual microphones pointing in all directions inside San Vitale

the pressure gradient X Y Z. The W channel (the mono signal) is the zero-order information, corresponding to a constant function on the sphere, while X Y Z are the first-order terms (the dipoles or figures-of-eight). This first-order truncation is only an approximation of the overall sound field. The higher orders correspond to further terms of the multipole expansion of a function on the sphere in terms of spherical harmonics. In practice, higher orders require more speakers for playback, but increase the spatial resolution and enlarge the area where the sound field is perfectly reproduced (up to an upper boundary frequency). The graphical analysis is performed by a Matlab program, which creates an animated colour video rendering of the sound map, plotted over the 360×180° panoramic image (Fig. 5).

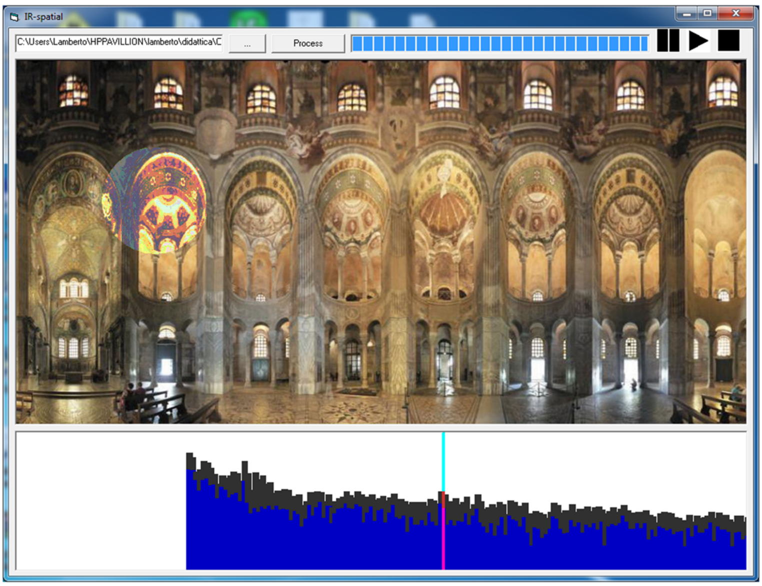

Fig. 5 Colour video rendering of the sound map over a 360×180° panorama of San Vitale's interior

Figure 5 shows the amplitude of a strong reflection from one specific position in San Vitale, and the corresponding reflection of the Impulse Response. The audible rendering is obtained by reprocessing the original Impulse Response recording - a new set of virtual microphones is extracted, one feeding each loudspeaker of the playback array. The directivity and aiming of each of these virtual microphones is obtained by solving a linear equation system where the signals re-recorded by placing the Eigenmike™ probe at the center of the playback system are maximally similar to the original signals recorded in the church. This method also corrects inherent deviations from ideality caused by the loudspeakers employed, both in terms of magnitude/phase response and of placement/aiming/shielding.

Acoustic Parameters in San Vitale

The archaeoacoustics (Scarre and Lawson 2006) of San Vitale has received recent attention (Knight 2010, 2013, 2014; Tronchin and Knight 2008; Tronchin et al. 2007). The acoustical character of a building is a qualitative assessment by means of 3D auralization and augmented reality of the quantitative calculations from Impulse Responses (IRs). These include the Reverberation Time (RT), the amount of resonance, presence of echo, perception of Clarity (C) and the absorption coefficients of various architectural materials comprising the interior space. For the purposes of understanding aurality in San Vitale an acoustic survey was performed in 2006 (Tronchin and Knight 2008; Tronchin et al. 2007) and compared with previous results (Fausti et al. 2003). The 2006 survey recorded the Impulse Responses in the frequency range 31.5Hz to 16000Hz, revealing a noticeable increase in Reverberation Time from 125 to 31.5Hz. This did not appear in the previous study as IRs were recorded only between 125 and 4000Hz (Fausti et al. 2003, Figs. 4 and 9).

From the recorded Impulse Responses (IRs) acoustical parameters were calculated (Tronchin et al. 2007) such as Reverberation Time (RT), from the decay range between −5 and −25 (RT20) and between −5 and -35 dB (RT30) (Fausti et al. 2003, p. 5). The average duration of RT30 and RT20 in San Vitale was identified as 4.70 s and 4.46 s respectively, both very long but not unexpected in a sensorially immersive interior sacred space intended as a place for congregating and liturgical ceremony (Tronchin et al. 2007).

A comparison was made between two types of acoustical Clarity (*Klarheitsmass*) calculated from the Impulse Responses recorded in San Vitale (Tronchin et al. 2007). Clarity C80 is related to musical perception, the time interval being limited to 80 milliseconds, and C50 is related to the perception of speech, with the time interval limited to 50 milliseconds (Tronchin and Farina 1997; Tronchin 2013). Musical perception in San Vitale is consistently clearer on average by about 3 dB. The reverberation tail caused low values of Clarity, also in agreement with other measured places of worship, greatly aiding in distributing singing throughout the entire church interior (Tronchin 2013; Tronchin et al. 2007; Tronchin and Farina 1997).

Considering the range of normal human speech to be between 125 and 8000Hz within the Reverberation Times RT20 and RT30, San Vitale revealed that at 125Hz the RT20 was 5.17 s and for RT30 it was 5.02 s. The same speech frequency range for the perceptible Clarity of speech (C50) revealed that Clarity was better at the top extreme of the speech range, with 2.92 dB at 8000Hz. Therefore, the most effective and intelligible speech in San Vitale is at the upper frequency range between approximately 4000Hz and 8000Hz, a higher pitch of spoken voice. The relationship exists where the deeper the voice, the less the perceptible Clarity and with increased reverberation, the least perceptible area being around 250Hz. Therefore, for normal speech in the mid-range the acoustics of San Vitale are not effective, but they are well suited for oratorical acclamation. In other words, the poor intelligibility of speech in San Vitale may have been compensated for by the speaker's choice of speech rate, articulation, and oratorical voice projection and intonation. It is therefore interesting to note that the resonant frequency of San Vitale's interior is 4Hz and that, if the officiating priest intoned on E the entire volume of air within the church would resonate. Whether this acoustical phenomenon was utilised in the sixth-century is not known.

The calculated RTs and Clarity were mapped across the plan of San Vitale [2; 3; 25], reporting Clarity C50 and RT30 as a result of a numerical evaluation of a 3D model of the church, properly calibrated with the experimental measurements and afterward modified by applying material changes made during the medieval period.

Visual Experiments in San Vitale

A series of lighting measurements were taken inside San Vitale to identify potential differences and similarities in the visual experience of the clergy and congregation. The daylight factors (DF) for indoor lighting and the design sky (DS) were evaluated and mapped for the entire church interior by means of the specialised software Ecotect™ (by Autodesk).

The light-levels, caused by natural external light, could be determined for specific positions within the church by means of the following calculation:

$$L_p = \frac{DF_p}{100} L_{ps} \tag{2}$$

Where L_p represents the light-level in the corresponding position, expressed in candles; DF_p is the daylight factor at position p and L_{ps} is the light-level of the sky.

Figs. 6 and 7 represent the light-level in the central space of San Vitale and also in its chancel and apse. The light-level for each window has also been calculated by considering the relative position of the sun to the windows. The following Fig. 8, shows the ground floor central windows of the apse, from which it is calculated that

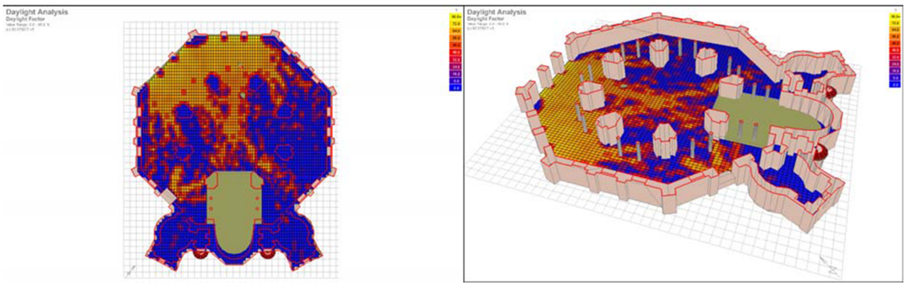

Fig. 6 Map of light-levels in the interior body of San Vitale (*left*). Isometric view (*right*)

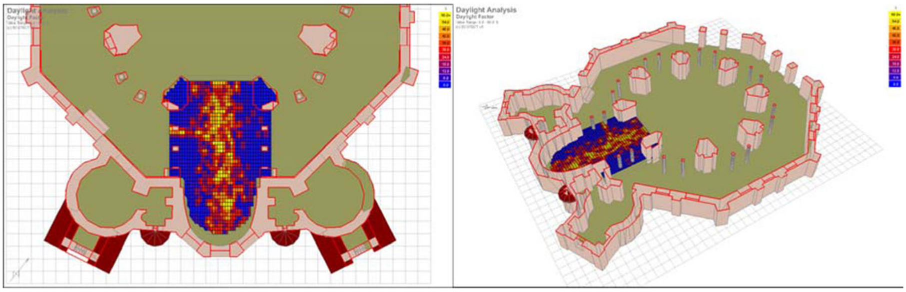

Fig. 7 Map of light-levels in the chancel and apse (*left*). Isometric view (*right*)

during the sixth-century, during the daylight hours between 7 AM and 1 PM, natural lighting illuminated at least 60 % of the total ground floor surface (calculated by means of Ecotect) for almost 10 months of the year.

The results of artificial lighting in San Vitale, by way of hanging oil lamps and candles, awaits further experimentation and analysis.

San Vitale's Original Glass Windows

The original glass windows of San Vitale were considered during the visual reconstruction of the church. The natural light entering the interior was substantially altered by the replacement in the sixteenth-century of the original coloured glass window panes with clear glass perhaps from Venetian workshops on the island of Murano. Also at this

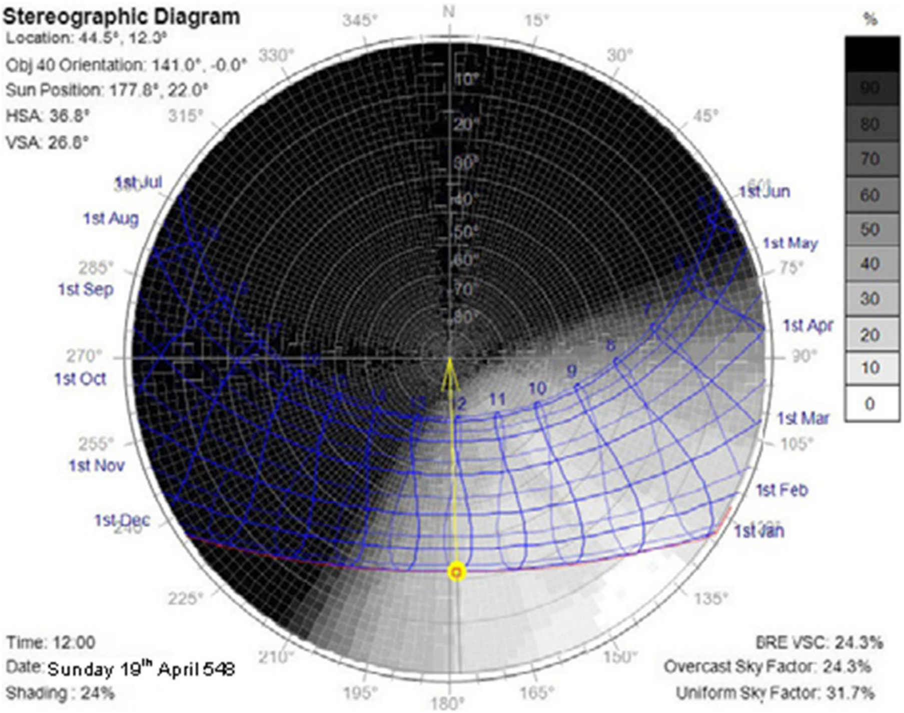

Fig. 8 Stereographic diagram with Ecotect analysis for Sunday April 19, 548 (dedication date of San Vitale)

time, the internal furnishings of the church were substantially altered, affecting what was being illuminated. To properly reproduce the sixth-century architectural interior and natural illumination, with the aim of understanding the visual impact that was encountered in the sixth-century, the original glass panels now close by in the Diocesan Museum collection at Ravenna have been analysed and a proposed original San Vitale window has been reconstructed (Figs. 9 and 10).

Revisiting San Vitale's History

The results presented above contribute to and amend our knowledge of San Vitale's historical context. The initial biography of this church has tended to be subsumed by

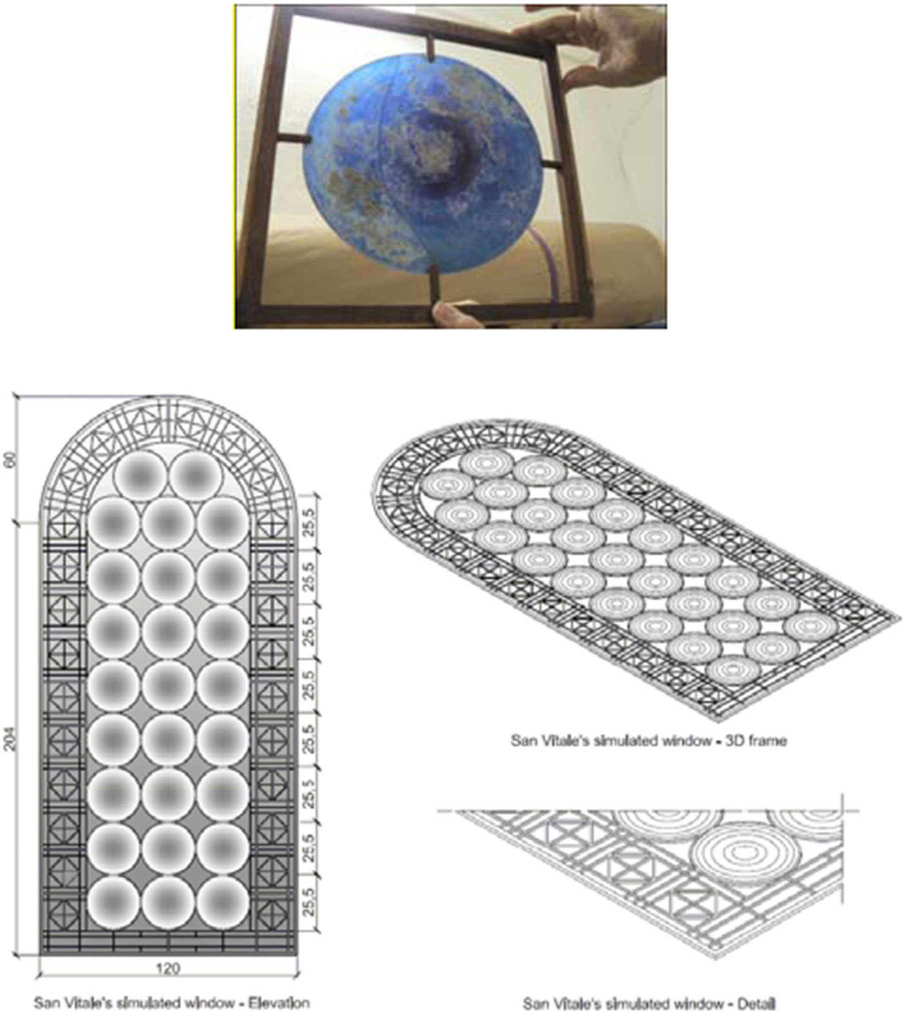

Fig. 9 An original coloured glass window disc from San Vitale (above) and experimental reconstruction of the church's original sixth-century window

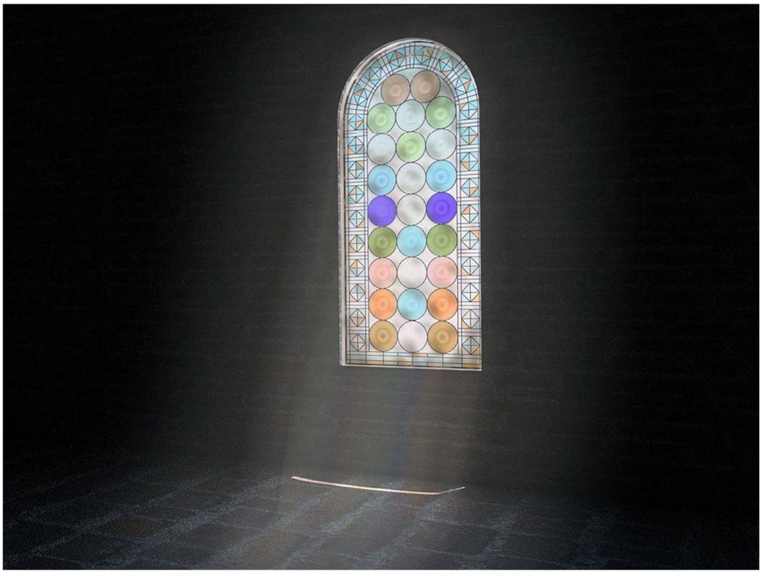

Fig. 10 Rendering of reconstructed sixth-century San Vitale window

the narrative of Justinian's drive to consolidate the western and eastern empires under Nicene Orthodoxy. The reign of Justinian (527–565 CE) has traditionally been seen as the cultural/political milieu into which San Vitale must be set. The famous apse wall mosaics apparently make it evidently clear that Justinian and his consort Theodora figured large in the raison d'être of this church. However, the original context in conjunction with the design, survey, construction and decoration of the church need to be fully taken into account.

Important clues help determine the construction progress of San Vitale, including the fact that the monogram of Bishop Victor (536–545 CE) only appears on the ground floor column capitals, likely indicating that by 545 CE (Krautheimer 1986, p. 232), the construction of the church had reached the height of the second storey. The name MAXIMIANVS above the mosaic figure of the bishop on the north chancel wall is a later replacement in stone *tesserae* (Deliyannis 2004, p. 186; Krautheimer 1986, p. 232), the original name may have been that of Bishop Victor. Focusing on the completion and dedication of San Vitale under Bishop Maximianus and Byzantine rule effectively subverts the intentions and achievements of the innovative design, survey and construction phases initiated by Ecclesius and continued by his successors Uricinus (533–536 CE) and Victor when Ravenna was the Ostrogothic capital.

The evidence presented here of San Vitale having borrowed layout features and measurements from the Arian baptistery is admittedly controversial, as it demonstrates contradictions with former interpretations of San Vitale's historical context, an example being Von Simson's statement that:

> 'After the general architectural plan had been laid down in Byzantium, its execution became the responsibility of the imperial representatives in Ravenna' (Von Simson 1987, p. 22).

The transformation of the octagonal geometry at the core of the Arian baptistery into the design of San Vitale physically and symbolically converts Arianism to Nicene Orthodoxy, an intentional message of Ravenna's sixth-century Nicene Orthodox community, or at least their bishop, that would have resonated not only in the western capital ruled by a predominantly Arian Ostrogothic court, but also an important political signal to Constantinople. It may also indicate a further depth to the rivalry between Nicene Orthodox and Arian communities of late antique Ravenna (Deliyannis 2010; Ward-Perkins 1984). It is known that Ecclesius visited Constantinople in 525/6 with Pope John I. The subject of this visit was to, on King Theoderic's orders, convince the eastern court to relax its proclamations against Arianism, which demanded that all Arians convert to Nicene Orthodoxy. The mission failed, perhaps intentionally. Returning to Ravenna in the spring of 526, John was imprisoned and died in detention there on May 18. Theoderic died only 3 months and 12 days later, on August 30th. Ecclesius may have found himself in more tolerable circumstances under the following regency of Queen Amalasuntha, who appears to have had an interest in Orthodoxy. It is at this time, or shortly following, that Ecclesius initiated the construction of his new churches at Ravenna. In this historical context, the "conversion" of the layout and polygons of the Arian baptistery into San Vitale reveals a high degree of intentionality. It may be that Ecclesius was influenced by architectural developments in the eastern capital as well as innovations local to Ravenna. Either way, the Justinianic building program that characterises discussions of sixth-century ecclesiastical architecture must be carefully reset in the case of Northern Italy, for, as Moffatt (1996) saliently pointed out, at Ravenna: "We are left with a rather distorted picture with an emphasis on the churches completed in the period of Orthodoxy after 540, at the expense of the building activity and patronage under Arian rule' (Moffatt 1996, p. 242)."

Conclusions

We have presented the results of several methodologies and experimental data that were part of the campaign to reconstruct an augmented reality for San Vitale, providing data not otherwise obtainable and contributing to a deeper understanding of the visual and aural attributes of this important sixth-century church. We have presented the results of aural and visual experimental methodologies employed at San Vitale, which together reveal important qualities of its meaningful and sensorial atmosphere.

Converting the metric measurements of San Vitale into the original Roman units has revealed key elements of the design were taken from an existing structure at Ravenna, the Arian baptistery. The creation of a virtual model of San Vitale revealed an important obscured aspect of its harmonious internal logic, the spatial distribution of column bases shapes. It has been demonstrated that although a number of San Vitale's key architectonic features were concealed, the overall conspicuous and sensorial impact of the interior communicates centrality and cohesion. The octagonal geometry of San Vitale also even extends to the temporal dimension of its dedication date on the Octave of Easter, April 19, 548. The evidence strongly suggests an intention to create a sacred space and place of congregation that makes logical sense but where the quantitative parts that combine to create a complex harmony are not necessarily intended to be observed beyond the perceived qualitative whole - where concord is expressed partly through embedded logical, yet abstruse details.

Therefore, San Vitale was designed, surveyed, constructed and decorated with sacred geometry in mind, most likely to evoke awe and mystery. The acoustic attributes and the ways in which natural illumination define the interior, along with the anagogic function of geometry in the vertical hierarchy of San Vitale's internal space combine as an effective expression of Euclid's *Elements*, especially the fifth *Common Notion*:

The whole is greater than the part (Gray 1989, p. 28).

The architect(s) of San Vitale achieved a meaningfully resonant and unified result by utilizing conspicuous and concealed design elements to create a whole, the entire sensorial and, therefore, qualitative experience.

Acknowledgments We would like to thank Prof. Simon Keay (Archaeology, University of Southampton), Dr Matthew Wright (Institute of Sound and Vibration Research, University of Southampton) for their support and interest. We are indebted to Monsignor Guido Marchetti (Opera di Religione of the Diocese of Ravenna), Dr. Maria Grazia Maioli (Soprintendenza per i Beni Archeologici dell'Emilia-Romagna), Dr. Anna Maria Iannucci (Soprintendenza per i Beni Ambientali e Architettonici di Ravenna). We would also like to thank Dr. Matthew Johnson, Dr. David Wheatley, Dr. Donatella Restani, Dr. Ilaria Durvilli, Dr. Maddalena Roversi, Dr. Eleftheria Paliou, Ioanna Giannakopoulou, Dominic Barker and Daniel J. Knight.

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