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VIRTUAL REALITY IN CHURCH ACOUSTICS: VISUAL AND ACOUSTIC EXPERIENCE IN THE CATHEDRAL OF SEVILLE, SPAIN

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Virtual reality techniques are applied to combine sound and visual perception within one of the most important heritage buildings in Europe: cathedrals, which are conceived as symbols of the European cultural identity. 3D models for visualisation and realistic pieces of sound are integrated into virtual reality environments to be used for the evaluation of the quality of the sound-field perception by means of subjective evaluation techniques, and to relate this data with on-site measurements, by using perception tests based on auralisation techniques. This paper shows the potential of virtual acoustic environments in research into church acoustics, by providing results of a preliminary experiment, in the Royal Chapel of the Gothic Cathedral of Seville, southern Spain, designed to ascertain which factors clearly influence immersion, such as loudness and the type of sound piece.
Keywords: virtual reality, auralisation, cathedral acoustics

1. Introduction

Since the pioneering research of Raes et al. [1] on the acoustical properties of two Roman basilicas, exhaustive pieces of work of experimental characterisation have been published in several European countries [2-4], with contributions involving various acoustic aspects [5,6]. However, there is currently a profound lack of subjective studies concerning the preferential listening conditions of the audience in these sacred spaces. According to Algargoosh [7], the physical measurements of architectural acoustics fail to precisely reflect the human acoustical experience in worship spaces. Aural architectural analysis includes perceptual and cultural aspects, in addition to the physical aspects, and provides a more comprehensive understanding of the aural experience in these places; another important issue is the strong correlation between audio and visual perceptual aspects.

Virtual Reality (VR) techniques enable humans to explore beyond and into the current situation, including computer technologies that use software to generate realistic images, sounds and other sensations that replicate a real or imaginary environment. Virtual reality recreations have often emphasized the sensory experience of sight and these have risen in importance for the visualisation of cultural and archeological heritage over recent decades [8], and have also been applied as a research methodology in many disciplines [9]. The keywords of acoustic virtual reality are *simulation*, *auralisation* and *spatial sound reproduction* [10]. The expression auralisation, introduced by Kleiner et al. [11] in 1993, is analogous to the well-known technique of visualisation, that is, it describes the process of audible performance.

Auralisations and textured visual models integrated in virtual reality software tools have been used by various procedures in a variety of religious scenarios describing several liturgical and cultural events. For example, Pedrero et al. [12] virtually restored a group of Spanish pre-Romanesque churches, and the simulated room impulse responses (RIR) were convolved with anechoic recordings of Mozarabic Chants; Garcia et al. [13] studied the change in acoustic conditions for performances of the Misteri d'Elx in the basilica of Santa Maria de Elche, by using simulated models of the basilica which were calibrated based on on-site measurements of acoustic parameters and of absorption coefficients of materials; Alonso et al. [14], by virtual reconstruction, acoustically studied the configurations adopted from the transept of the Seville Cathedral for concert halls; and Postma et al. [15] presented not only the calibration method of acoustical models for virtual reality auralisations on historical sites, but also an overview of the various essential elements necessary to achieve an immersive VR experience of the symphonic concert held in Notre Dame Cathedral on the occasion of its 850th anniversary [16]. This research group [17] also examined the perceptual quality achievable by room acoustic simulations by means of listening tests for three historical sites.

This paper provides the results of a VR experience in the Royal Chapel of the Gothic Cathedral of Seville. The paper briefly describes the processes of creation of its texturized visual model and the calibration of its acoustic model. The validation of the auralisations generated from the simulated RIR was carried out by preliminary listening tests, both in terms of comparison with those generated from the measured RIR and in terms of overall impression.

2. Research methodology

The methodology applied for the acoustic recovery of sound heritage of worship buildings is mainly based on four tasks: the current acoustic analysis of the space, which involves a rigorous measurement campaign to register a comprehensible set of RIR; its acoustic modelling and simulation to generate a sufficiently reliable set of RIR; the generation of auralisations both from measured and simulated responses; and the visual modelling of the interior of the temple to complete the immersive experience and support the auralisation.

Not only will the quality achieved in each task determine the reliability of the virtual environment, but it will also provide a means for their integration in the same context.

2.1 Acoustic measurements

Room impulse responses were registered following both the recommendations of the ISO 3382-1 [18] and the specific guidelines published for worship spaces [19,20].

In the Royal Chapel, 1 source position (located on the symmetry axis at the high altar) and 3 receiver points (distributed throughout the pew area) were considered. It should be noted that the acoustic characterisation of this chapel was part of a more extensive experimental campaign carried out in the cathedral of Seville, where 5 source positions and 30 receiver points were included.

WinMLS2004 software tool was utilised for the processes of generation, acquisition and analysis of the RIR, by means of an EDIROL UA-101 sound card. The excitation signal was reproduced in the enclosure through an AVM DO-12 omni-directional source, previously amplified with a B&K type 2734 power amplifier. Each RIR was captured with an Audio-Technica AT4050/CM5 multi-pattern microphone both in its omni-directional and bi-directional configuration (figure-of-eight), connected to an Earthworks-LAB1 polarisation source. Sine-swept signals were used as excitation signals, whose frequency range and duration were adjusted both to cover the octave bands ranging from 63 to 16,000 Hz as well as to achieve a signal-to-noise ratio higher than 45 dB for all the octave bands of interest. Environmental conditions were monitored during the measurement session, and registered an average temperature and relative humidity of 24° C and 46%, respectively. An equivalent background noise level of 30.7 dBA was recorded with a SVANTEK958 analyser. All the measurements were carried out in the unoccupied temple, at night time. Spatially and spectrally averaged values of the main acoustic parameters measured in the Royal Chapel are listed in Table 1.

Table 1: Spatially and spectrally averaged values measured in the Royal Chapel

T_{30m} (s)	EDT$_m$ (s)	T_{Sm} (ms)	C_{80m} (dB)	D_{50m} (-)	G_m (dB)	L_{Jav} (dB)	J_{LFm} (-)	STI (-)
3.75	3.54	190.25	-0.46	0.40	5.59	-1.99	0.17	0.52

2.2 Acoustic modelling and simulation

Simplified virtual models of the Cathedral of Seville and the Royal Chapel of this temple (Fig. 1, right), with an approximate interior volume of 200,000 m^3 and 10,970 m^3 respectively, were created by using SketchUp 3D modelling software. Acoustic simulations were carried out with CATT-Acoustic v9.1a, a software tool based on diverse geometrical acoustic algorithms, and the calculations of the acoustic parameters were obtained with the TUCT v1 engine tool, in which the "*longer calculation, detailed auralization* algorithm (#2)" was selected. The number of rays was manually determined at 300,000 both for the cathedral and the chapel, while the time considered for the truncation of the impulse response was estimated by bearing in mind the measured reverberation time: 7 s and 6 s, respectively. More details on the simulation of the main temple of the cathedral of Seville can be found in [14].

The acoustic characterisation of the models was mainly based on the assignment of absorption and scattering properties to each surface. Thus, a calibration process of the non-tested material coefficients (mainly stone) was developed in order to ensure that the model reproduces the current acoustic conditions. The scattering coefficients were determined in three different categories adopted depending on the irregularities and the degree of decoration found on each surface. The process concluded when the simulated reverberation time in frequency band, spatially averaged, differed less than one JND (5%) from the corresponding onsite measured values. Due to the complexity of these models, it was decided to consider in the adjustment the point-by-point values at each frequency band of other acoustic parameters such as EDT, C_{80}, and T_S.

Specifically, the model of the chapel has been refined until more than 80% of the simulated values obtained for the considered parameters differ by no more than 2 JND from the measured values.

2.3 Auralisations

According to Vörlander [10], auralisation is "the technique of creating audible sound files from numerical (simulated, measured, or synthesized) data". Binaural room impulse responses (BRIR) are essential for the generation of auralisations through their convolution with anechoic signals. These impulse responses can be depicted as filters, since they incorporate additional information into the omnidirectional response of the room such as the source directivity, the head-related transfer functions (HRTF), and the equalization for the sound-reproduction system of choice (headphones, loudspeakers...). Simulated BRIR were calculated in the binaural post-processing module of TUCT, by using the ITA1_plain_44.DAT and the SENNH_HD600_plain_44.DAT headphone equalization filter. The convolution with the anechoic source signals was completed in the MultiVolver tool. In this case, each BRIR was convolved with brief extracts of three anechoic signals: a bible speech (20 s); a cello piece (40 s); and choral singing (40 s). It should be taken into account that it is necessary to calibrate the RMS level of the auralised wav-files before their reproduction, since the *convolver* auto-scales each wav-file for maximum dynamic range.

An additional validation of the auralisations by means of listening test is required, together with the previous calibration of the acoustic simulation model, by verifying the accuracy of the values of the acoustic parameters obtained in simulations with those obtained from the measurements made on-site. To this end, a previous assessment of the auralisations generated from the simulated RIR was performed through a subjective comparison with those generated from the measured RIR. Twenty-seven subjects (20 men and 7 women, with ages ranging from 29 to 80 years old, of whom 70.4% had no previous experience with auralisations) participated in this listening survey, which required a feedback process until the auralisations generated from the simulated RIR were considered to be sufficiently realistic. In order to ascertain whether a perceptual difference can be found between the stimuli auralised through the measured and the simulated RIR, the survey included 2

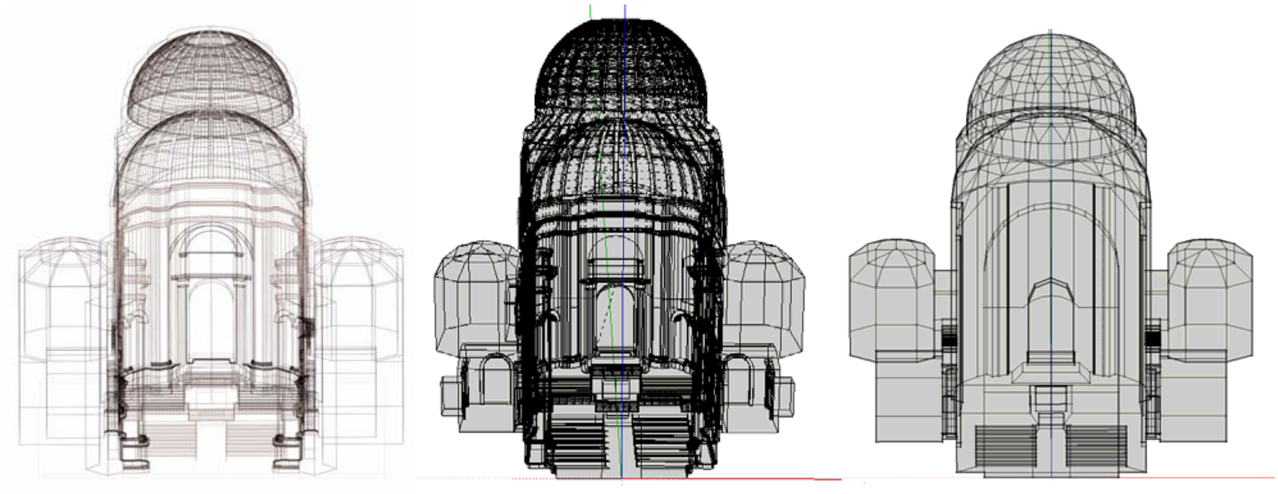

Figure 1: Geometrical model before simplifications (left); simplified visual model (centre); and simplified acoustic model (right).

multi-choice questions: a question based on a multi-comparison of 3 stimuli in which the listener had to recognise 2 of which were identical; and a perception question to indicate which stimulus (or pair of stimuli) caused a more reverberant sensation. Results showed that only 55.6% of participants recognised which of the two stimuli were the same, which indicates that the auralisation generated from the simulated RIR reproduce the real acoustics of the space with reasonable accuracy. Furthermore, 52% of participants were revealed to have the same perception of reverberation when listening to the auralisations generated from the simulated or measured RIR.

2.4 Visual model

A 3D visual model of the Royal Chapel of the Cathedral of Seville was created in parallel to the acoustic model described in Section 2.2 for the sake of its introduction into a VR software tool. The incorporation of auralisations into this visual model allows users to be immersed in the reproduced space that emulates the real experience, without being physically in situ.

The 3D visual model of the chapel was created by using several modelling software tools. The detailed geometrical model (Fig. 1, left) was previously drawn in Autocad 2014, resulting in 31,349 polygonal regions and 740 complex surfaces (implying more than 400,000 entities). In order to introduce such a model into the VR software, it was necessary to reduce its complexity by using the SketchUp modelling tool, with which it was possible to simplify the model to 115,152 entities or simple polygons (Fig. 1-centre), making possible a more efficient data processing.

Additionally, tool textures were added based on real photos of the interior of the building. Finally, the textured simplified model (Fig. 2) was imported from SketchUp into the World Wizard 5 VR software, which is a powerful tool for the rendering of the virtual environment, since it integrates the visual model, users' tracking, and auralisations.

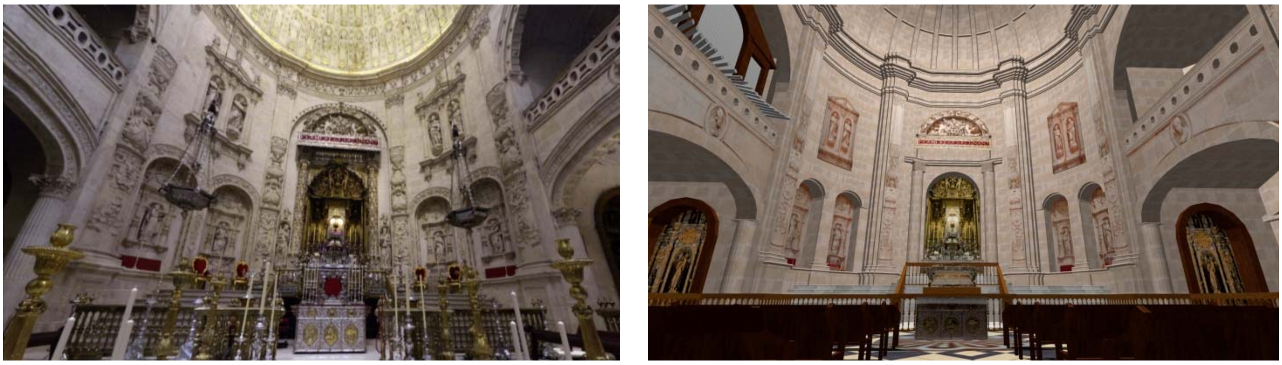

Figure 2: Picture of the Royal Chapel of the Cathedral of Seville towards the altar (left) and similar view in the VR simplified model (right).

3. Preliminary listening tests

Multi-modal virtual reality involving acoustic and visual features of the Royal Chapel of the Cathedral of Seville was employed to achieve the sensorial immersion of the spectator in the room under study. Such a virtual immersion allowed us to perform subjective listening tests in a controlled environment so that perceptually valid results could be attained.

With the aim of ascertaining not only the acoustic sensation of the processed auralisations, but also the visual impression produced by including the virtual model, a survey was designed following the specific bibliography and previous experiences of the research group [21,22]. The survey, with a total of 46 questions, was divided into 3 blocks: blind acoustic perception; visual virtualization aspects; and virtual acoustic perception including visual representation. All questions had a similar scoring scale with 5 possible answers (from 1 to 5), and also included a not-answering score (0). The answers rated with 0 were excluded in the calculation of the average values.

The first part of the test, "*Block A: Blind acoustic perception*", was performed by hearing the auralisations without any visual representation of the room. Aspects related to the acoustic qualities and the spatial perception of the space were analysed after listening to each stimulus, as well as the global perception of the space after listening to all of the stimuli.

The second part, "*Block B: Visual virtualization aspects*", referred to aspects related to the visual experience of the virtual environment, but without any auralisation included. Questions on the level of architectural details, the lighting of the space, and the fluidity of movement were included.

Finally, the third part, "*Block C: Virtual acoustic perception including the visual representation*", presented the complete virtualization, including both visual and acoustic aspects. The procedure was the same as in Block A, but included the visual model in this case.

A section of "*Comments*" was also included, in which the participants could provide some notes.

In the light of the results, the validation tests described in Section 2.3 and the auralisations of the 3 short sound pieces mentioned in that section, which were all generated from the simulated BRIR, were used for the virtual experience together with the visual model described in Section 2.4.

Listening tests were carried out in a quiet room and participants were accompanied by a technician during the tests to control their correct execution. Sounds were emitted through high-quality Sennheiser HD600 headphones, and a projector was used for the visualisation of the virtual model.

4. Results and discussion

Researchers and students of the School of Architecture of the University of Seville, some of which have knowledge in physical acoustic and room acoustic language, were selected as participants for the listening test. Thirty-three volunteers with normal hearing, 17 men and 16 women, ranging in age from 19 to 62 years old, participated in the listening test. It must be mentioned that approximately 70% of these participants had no previous experience with VR environments.

Once the tests were finished, the results were carefully processed to enables the methodology followed in each part of the process and the virtual experience itself to be validated.

4.1 Reaction to different stimuli

A significant part of the questionnaire was designed with the aim of analysing the variability in the acoustic perception of the space when listening to different types of sound pieces.

From the answers of the first part of the test entitled "*Block A: Blind acoustic perception*", the results showed that, as expected, the perceived reverberation of the space significantly changed with variation of the stimulus: while most of the participants ranked the reverberance of the space as *low-moderate* both for music and choral singing (75.8% and 66.6% respectively), more than 80% of listeners found the chapel as *highly* or *very highly* reverberant for word transmission. However, for questions on the perceived clarity, similar results were obtained for all the pieces: this characteristic ranked as *high-very high* for about 80% of participants, especially when only music was involved. Regarding the feeling of envelopment, sounds appeared to be perceived from all directions for the 3

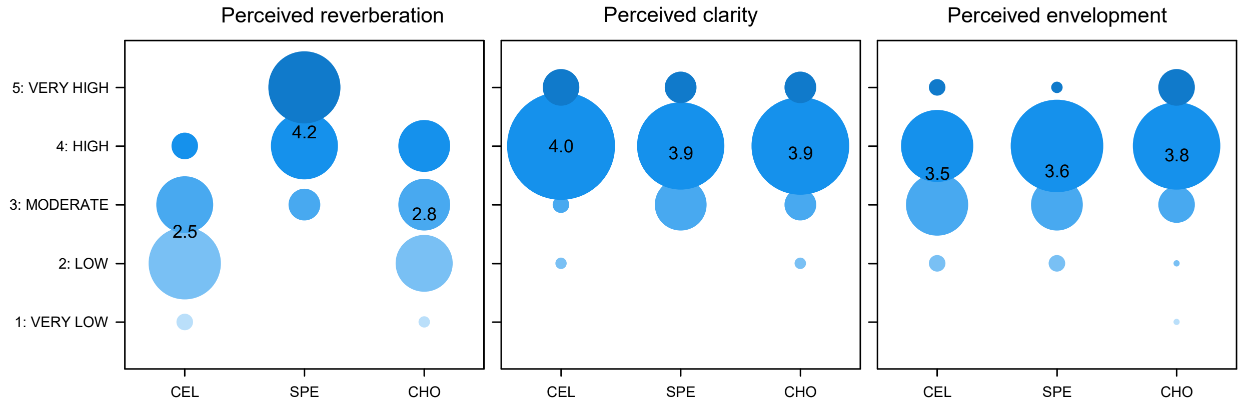

Figure 3: Listeners' perception of the reverberance of the space (left), of the clarity of the message (centre), and of the feeling of envelopment (right), in response to the three types of stimuli: Cello piece (CEL); male speech (bible reading) (SPE); and choral singing (CHO).

pieces, and caused a *moderate-high* feeling of envelopment that was stronger when listening to the choral singing, whereby 20% of participants affirmed that they experienced a *very high* feeling of envelopment. These results are graphically shown in Fig. 3, in which the size of the bubbles represents the number of listeners that chose each option (ranking specified along the vertical axis), and the number corresponds to the mean value obtained in the different questions. Furthermore, it must be mention that the perceived source-receiver distance was greater when listening to the choral piece, despite the fact that all the stimuli were pre-processed to be reproduced with the same perceived volume by using a specific audio software tool.

As can be observed in Table 2, significant differences appeared when the participants were asked to rank the acoustics of the space after listening to each sound piece. While 91% of subjects classified the acoustics of the chapel as *good-very good* for instrumental and choral music, more than 75% of subjects ranked it as *poor-moderate* for speech.

Table 2: Percentage of participants that ranked the acoustics of the space in each interval of the provided scale

Stimuli	Bad	Poor	Moderate	Good	Very good
CEL	0.00	6.06	3.03	69.70	21.21
SPE	3.03	30.30	45.45	18.18	3.03
CHO	0.00	0.00	9.09	63.64	27.27

4.2 Overall listening experience: feeling of immersion

Before evaluating the feeling of immersion caused by both the visual environment and the auralisations, participants were asked to independently evaluate the quality of the visual model. The results indicated that there are no differences when judging visual aspects of the virtual model: neither does it depend on whether the participants have previous experience as users of VR environments, nor does it depend on whether the participants recognise the space under evaluation.

As can be observed in Fig. 4, the majority of the participants positively evaluated the visual model. Specifically, more than 80% of them rated the visualisation in general terms as *good-very good*. They were also asked about certain specific aspects: lighting, which was rated as *good* by almost 60% of participants; fluidity of movement, which was rated as *good-very good* by 94%; and the degree of detail from the architectural point of view, which was considered as *good-very good* by 62.5% of the people surveyed, despite the degree of simplification required by the software.

Once the visual model and the auditory experience had been separately assessed, both were combined to immerse users in the virtual environment. At this point, participants' impressions when listening to the 3 sound pieces were used to analyse their overall listening experience, and also to assess whether the inclusion of the visual aspects implied significant variations in their opinions with respect to the answers they provided after the "blind" part of the test.

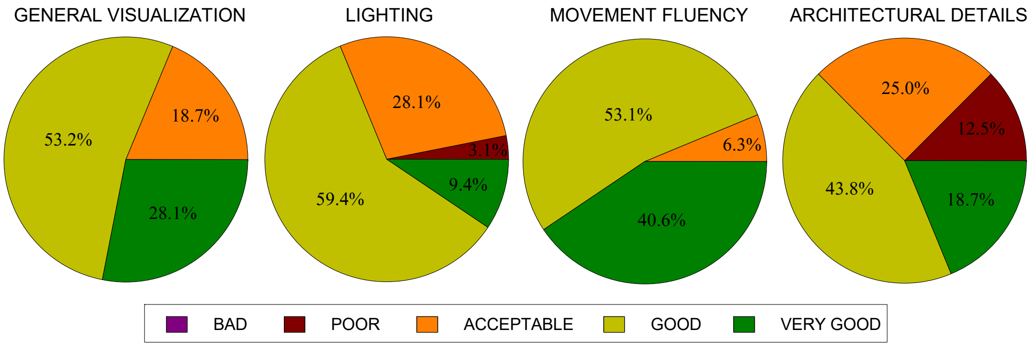

Figure 4: Participants' evaluation of several aspects of the visual model.

After listening to the three sound pieces with visual support, the pattern of the results given by the participants do not vary significantly from those obtained in block A (Fig. 5). However, it is worth mentioning that the reverberance is the acoustic characteristic that is mostly affected by the incorporation of the visual environment, since the perceived reverberation level is ranked slightly lower (the mean value given for the feeling of reverberance is reduced by 1%) in block C.

5. Conclusions

In this paper, a VR experiment in the Royal Chapel of the Cathedral of Seville was carried out to perform initial listening tests, both to evaluate the procedure of the creation of the virtual environment, and to assess the acoustic perception of the space in response to different stimuli.

The first listening tests validated the auralisations generated from the simulated RIR, which allows the use of these signals in VR environments.

The perception questionnaire showed that the perceived reverberation of the space significantly changed with the stimulus, whereby it was acceptable for music and choral singing but very reverberant for word transmission. These results are in close agreement with the recommended values of the reverberation time and measured values of T_{30} and EDT (Table 1). Nevertheless, the perceived clarity and the feeling of envelopment barely vary with stimulus. Listeners perceived the sound pieces with great clarity and from all directions, which is in accordance with the C_{80}, D_{50} and STI measured values and L_J and J_{LF} measured values, respectively (Table 1).

The results recovered in this experiment provide the authors with useful guidelines for the continued work on virtual reality environments of heritage buildings, and also with substantial considerations for the design of future perception tests. Furthermore, the participants' comments reveal that greater efforts must be made to incorporate psychoacoustic factors into the survey, since they have proven to be highly influential in the results.

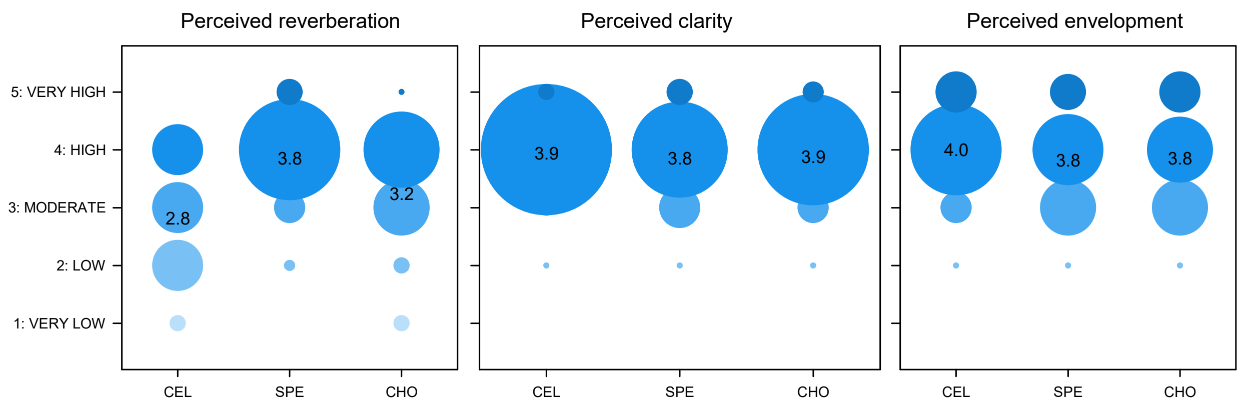

Figure 5: Listeners' perception, including visual environment, of the reverberance of the space (left), of the clarity of the message (centre), and of the feeling of envelopment (right), in response to the three types of stimuli: Cello piece (CEL); male speech (bible reading) (SPE); and choral singing (CHO).

The research group is currently working on a room specially designed for the performance of listening tests and have acquired sophisticated equipment for VR environment reproduction. Additionally, visual models of other cathedrals are being modelled and anechoic stimuli typical of these spaces are being recovered, such as musical pieces played by the Baroque Orchestra of Seville.

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