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Seeking differences between architects' and acousticians' concert hall assessments

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ABSTRACT:

By auditory and visual assessment, we investigate whether architects and acousticians describe their perception of concert hall acoustics in the same language. Four concert halls were represented in controlled in virtual reality environments. A total of 43 participants (23 acousticians, 20 architects–all with experience and interest in concert hall acoustics) participated in the experiment. During the experiment, all the participants were exposed to audio and video excerpts in two different positions across the four concert halls. An individual vocabulary profiling method (IVP) was used to collect the participants' attributes and textual ratings of the virtual spaces. The data were further analyzed via hierarchical multiple factorial analysis. The results reveal significant distinctions in the perceptual vocabulary and evaluation strategies employed by the two groups of professions, quantifying the perceptual dimensions without consensus vocabulary. They reveal a quasi-bidimensional perception space on architects using visual attributes and on acousticians using auditory attributes, but a higher perception space for the inverse modalities. Finally, the correlation between subjective and objective acoustical parameters reveals discrepancies between both expert groups on which objective parameter correlates with subjective balance and timbre, while it shows agreement for other subjective parameters.

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I. INTRODUCTION

Designing concert halls is a cross-disciplinary effort of cooperation and communications between *acousticians* and *architects*, who often have different priorities and preferences (Muckenhirn, 2012). In the design phases, the imagination of the designed space could differ according to the receiver's profession; acousticians might be more sensitive to tiny audible details (Neidhardt *et al.*, 2022). On the other hand, Liu *et al.* (2021) stressed that architects tend to focus mainly on controlling the physical parameters of the acoustic environment, such as reverberation time, sound pressure level (SPL), and speech intelligibility. These investigations highlight fragmented efforts to study the differences in sound perception between occupations for general-purpose spaces. A robust and reliable method is needed to compare concert halls in order to facilitate the communication between acousticians and architects.

To examine how spaces can be qualified, the previous works in Llorca-Bofí *et al.* (2022) and Llorca-Bofí *et al.* (2023) used individual vocabulary profiles (IVP) that categorize into different groups of visual and auditory descriptors of the urban soundscape. The studies have suggested that, overall, the auditory descriptors are less consensual definitions than visual descriptors. However, they were neither addressing the differences between individual participants nor descriptor clusters.

In this study, we propose a methodology that compares auditory perceptions of two panel groups—architects and acousticians—in four virtual concert halls. The visual and auditory stimuli of concert halls were reconstructed using the spatial impulse response data measured in Pätynen *et al.* (2008c) and images taken by Llorca-Bofí *et al.* (2025). We aim to quantify the perceptual differences between the four concert halls, the relations between descriptors, as to how they differ between *panels* of *architects* and *acousticians* with hierarchical multiple factorial analysis (HMFA) (Le Dien and Pagès, 2003).

II. BACKGROUND AND CONTRIBUTION OF THIS WORK

On one hand, while *in situ* listening to concerts yields the most reliable and natural perception, it presents challenges for comparative analysis across different halls. The data analysis of structured questionnaires can be complex, and at times, unfeasible, due to delayed comparisons, simultaneous variation of numerous parameters, non-identical stimuli, and the mood of the subjects. Kürer *et al.* (1969) and Schroeder *et al.* (1974) were among the first researchers to

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facilitate instant comparisons of concert halls through the application of binaural technology. Furthermore, Schroeder *et al.* (1974) enabled the comparison of halls under laboratory conditions by employing anechoic recordings played back via loudspeakers positioned on stage. Later, room acoustics simulations were utilized to comprehend descriptive attributes. Soulodre and Bradley (1995) convolved measured impulse responses (IRs) with anechoic signals to generate controlled stimuli for listening tests. A limitation of these studies, however, is that one or two sources on stage do not adequately represent a full symphony orchestra (Rindel *et al.*, 2004). In this regard, the studies of Lokki and colleagues (Lokki *et al.*, 2011; Lokki *et al.*, 2016; Pätynen *et al.*, 2008c; Pätynen *et al.*, 2008a) combined a loudspeaker orchestra to measure IRs and convolve them with individual instrument anechoic recordings. The approach carefully reconsidered the variability of the musical piece and the listener position using advanced spatial sound recording techniques. The recordings were subsequently reproduced in a laboratory setting, allowing for a simultaneous comparison of all samples. Building on this existing literature, the current investigation adds the visual representation of the room to the laboratory setting. Up to this date, there have been very few studies on the assessment of common vocabularies of concert halls using immersive acoustic and visual representations. For example, Ottley and Chen (2024), Chen *et al.* (2023), Chen and Cabrera (2021), used rendered visual three-dimensional (3D) models and show promising results in combining both immersive acoustic and visual simulations.

On the other hand, descriptive analysis (DA) techniques are founded on the quantitative characterization of a set of stimuli; numerous methods exist for the development of perceptual attributes and rating scales. Bech and Zacharov (2007) reviewed such methodologies and their applications in audio quality evaluation. Generally, DA employs consensus vocabulary techniques wherein a panel of assessors develops a set of attributes and reaches agreement on their definitions. However, panel discussions can be labor-intensive and time-consuming, presenting practical challenges. To mitigate these issues, individual vocabulary techniques have been introduced to reduce time and resource demands. In these techniques, each assessor generates their own set of attributes for stimulus evaluation. The utilization of individual attributes addresses the challenge of predefined attribute interpretation. Techniques classified under individual vocabulary include free-choice profiling (Williams and Arnold, 1985; Williams and Langron, 1984), the Repertory grid technique (Thomson and McEwan, 1988), the Flash profile (Delarue and Sieffermann, 2004), and IVP (Lorho, 2007). Based on the findings of these studies, Weinzierl *et al.* (2018) elaborated a more accurate and concise list of relevant factors of acoustic impression, limited to blind exposition of stimuli.

The current study aims to bring together both knowledge fields—high quality immersive auditory and visual representation of concert halls in VR—and use these representations to seek differences from architects' and acousticians' assessments using an IVP approach. The authors used the proposed approach already in a previous study (Heck *et al.*, 2025), which has been used as the basis for the current methodological setting.

III. EXPERIMENT SETUP

A. Concert halls

Four halls were selected for the study. The selection was made to ensure variability in both acoustic features and visual appearance. However, the interior design and decoration were not supposed to appear historical. Instead, the halls were chosen to follow a modern aesthetic language as this is assumed to be more relevant regarding the design of new halls. The four halls were the Cologne Philharmonie (CP), the Philharmonic hall in Munich's Gasteig (MG), Lahti Sibelius Hall (LS), and Beethovensaal in Stuttgart's Liederhalle (SB). As shown in Fig. 1, two receiver locations (i.e., listener positions) have been selected in each hall for evaluation. Receiver 1 ($R1$) is located closer to the stage while receiver 2 ($R2$) is always further back. This selection of two receiver locations per hall should allow for some variance in the listener perception not only between halls but also within a room. Rooms and positions are depicted at Fig. 2.

B. Acoustic capture

Spatial IRs provide the basis for the analysis in this study. The IRs have been measured in the selected halls during a measurement campaign by Lokki *et al.* (2011) in August 2010 (LS) and November 2012 (MG, SB, CP). The loudspeaker orchestra introduced by (Pätynen *et al.*, 2008c) has been used to represent distributed acoustic sources on stage, mimicking the instrument placement of a symphonic orchestra. As receiver, a GRAS vector intensity probe (GRAS Sound & Vibration, Holte, Denmark) has been used to allow for a spatial acquisition of the sound field in the positions denoted by Fig. 1. The resulting room IR database contains transfer paths between each emitter–receiver pair. For the purpose of this study, the measured spatial room IRs have been postprocessed according to the spatial decomposition method (Tervo *et al.*, 2013) and encoded into fourth-order Ambisonics B-format (Sennheiser Ambeo microphone, Sennheiser Electronic GmbH & Co. KG, Wedemark, Lower Saxony, Germany). Based on the recorded IRs, the room acoustical parameters (RA) $T30$, and early decay time $C50$, $C80$ have been extracted (Fig. 2).

C. Visual capture

For the visual representation of the rooms at the listener positions, each room has been captured with 360° photographs. For this purpose, a Kandao Obsidian camera (Kandao Technology Co., Ltd., Shenzhen, Guangdong, China) was placed on the seat of each listener location under study (Fig. 1). The camera position should correspond approximately to the head height and the resulting viewing perspective of an average adult sitting on the chairs in each of the concert halls. Thus, the camera with its six lenses, distributed equally on a horizontal plane, was positioned to 80 cm above the seat

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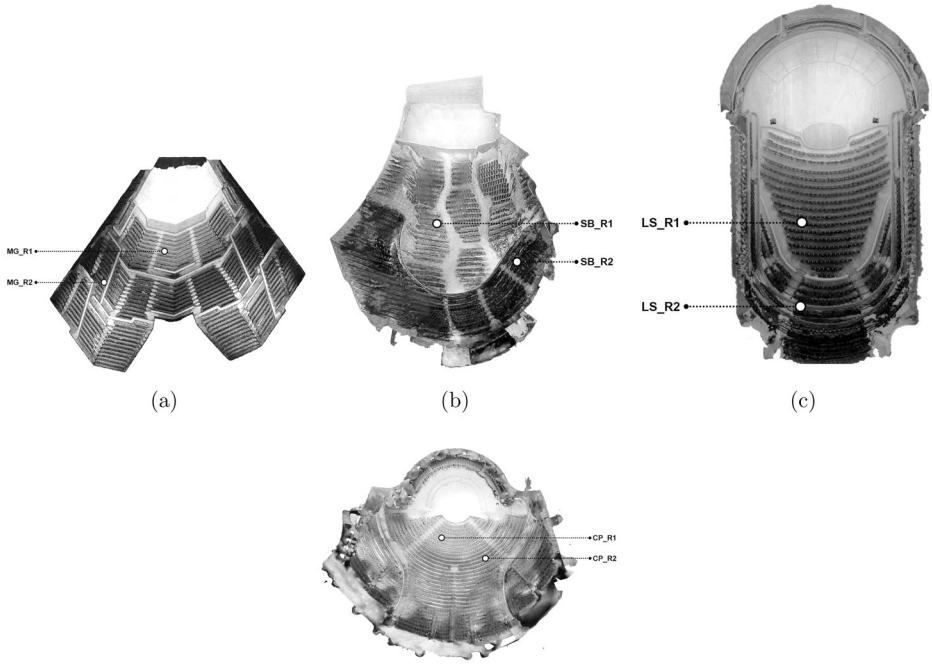

FIG. 1. Listener positions and concert halls.

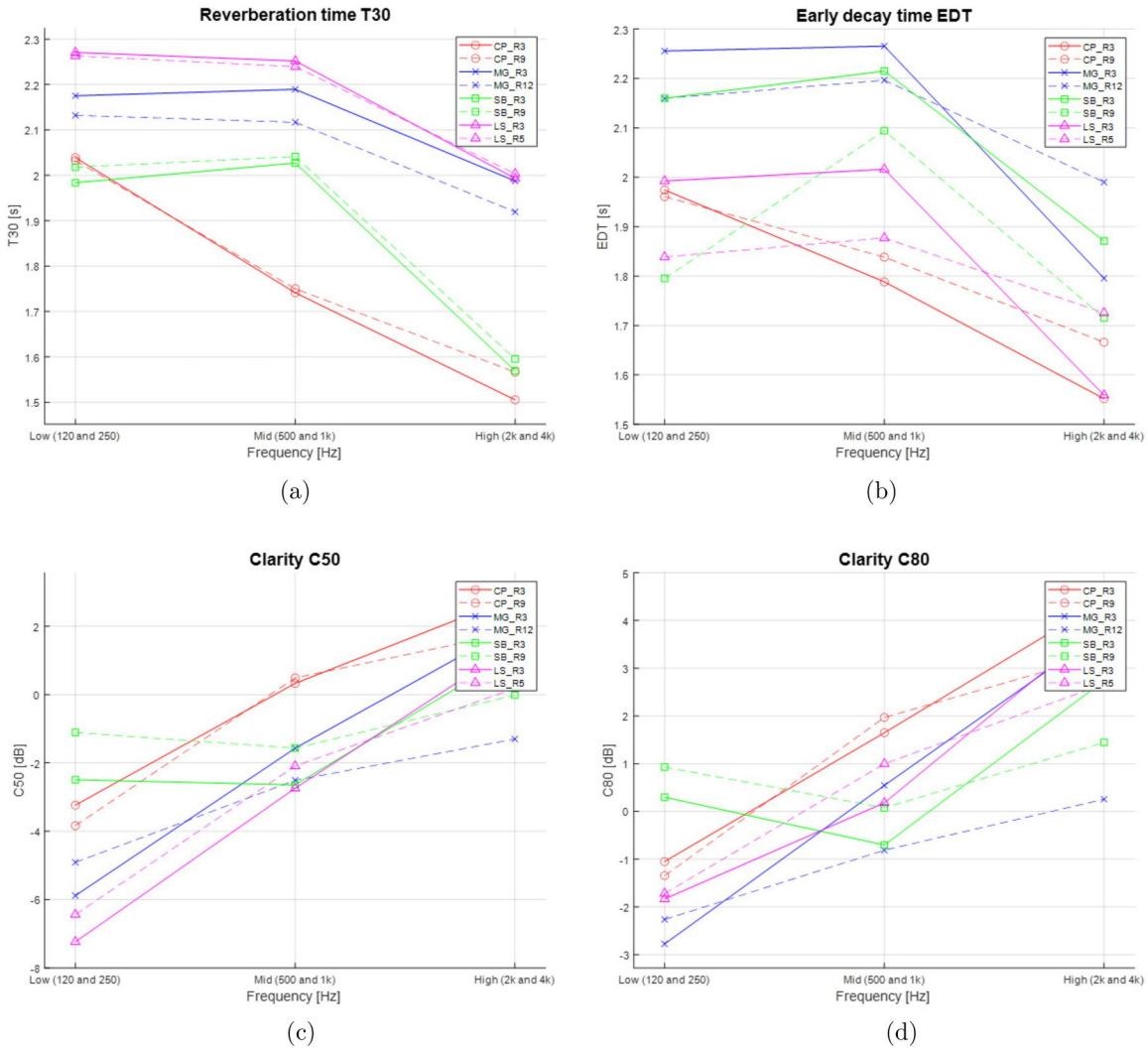

FIG. 2. Room acoustical parameters of the selected listener positions in the concert halls.

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level. Due to different chair designs, the camera height from floor level varied within and across rooms between 105 and 120 cm. During image capture, the camera settings were kept close to a reference setting as follows: amplification of the signal according to the scale defined by the International Organization for Standardization (ISO) = 200; shutter time- = 0.5 s; aperture = F/2.4; temperature = 3800. However, several photographs were taken with slight variations to the reference setting in order to fit the actual dynamic range. While ISO, as well as aperture values, were fixed, shutter time was adjusted because this parameter had a major impact on the pictures' brightness, without directly affecting the colors (Doeffinger, 2009; Naccari *et al.*, 2005). The shutter speed was always below 1/50 s to avoid sudden changes in color temperature due to flickering lights.

In order to adjust the small differences between photographs, a reference image was selected for each room, to which all other photographs of that room were matched. The color matching postprocessing included the changes in luminance, color range, and neutralization of color cast. For this purpose, the Color Match tool from Adobe Photoshop (Adobe Inc., San Jose, CA, USA) was used, which performs very similarly to the approach of Reinhard *et al.* (2001), as it maintains the mean and standard deviation of the color distribution of the reference image (Oskam *et al.*, 2012). When the photographs of the camera's six individual lenses were stitched together to one 360° picture, the files were stored as monoscopic pictures in .jpg format. The postprocessed pictures have an image size of 8760 × 2880 pixels. For the display in the virtual reality (VR) environment via head-mounted display (HMD), the bitrate was increased from 24 to 32 and the resolution was up scaled to 15 360 × 8640 pixels. Subsequently, it is saved in high dynamic range (HDR) format. A database containing the photographs of the receiver locations used here as well as further additional positions in the four concert halls can be found at Llorca-Bofí *et al.* (2025).

D. Virtual reality environment and stimuli reproduction

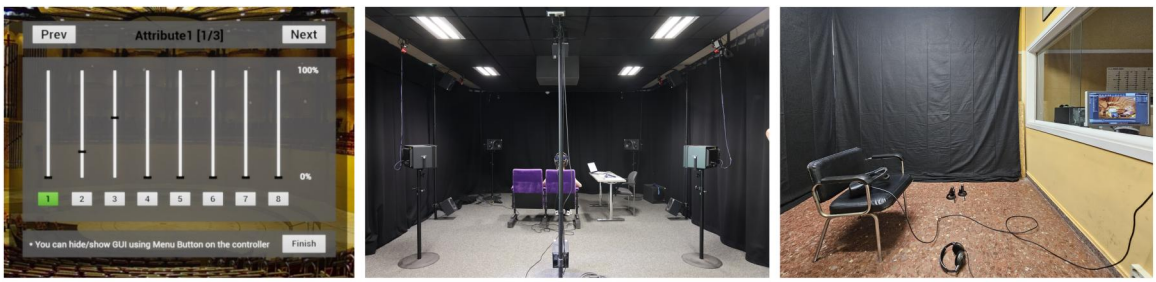
The experiment has been conducted in two laboratories: the acousticians' data were collected at the VR laboratory of the Institute for Hearing Technology and Acoustics, RWTH Aachen University; the architects' data were collected at the VR laboratory of the Department of Architecture, Universitat Politècnica de Catalunya. Both VR laboratories consist of one silent room with low illumination. The participants were seated in an upholstered chair comparable to a typical seat in a concert hall (Fig. 3). The following hardware was used:

- A HMD (sometimes referred to as VR glasses), HTC Vive Pro (HTC Corporation, New Taipei City, Taiwan)
- A pair of corresponding wireless controllers for user input.
- A pair of headphones, Sennheiser HD650 (Sennheiser Electronic GmbH & Co. KG, Wedemark, Lower Saxony, Germany).
- A Windows personal computer (PC) with i7-12700K Intel CPU processor and Nvidia graphics card (Nvidia Corporation, Santa Clara, CA, USA).

The framework for the visual reproduction has been built in Unreal Engine (UE) to which the eight 360° pictures in HDR format have been imported as so-called high dynamic range backdrop images (HDRI). These are HDR images that are spherically projected as a backdrop onto a background mesh. The projection mesh is a sky dome with the virtual actor (i.e., viewer) position at the center of the dome. The actor height was adjusted to the actual floor level around the subject when situated in the VR laboratory. In the UE project, each photograph, and its backdrop were placed in a separate *level* while all backdrops have the same center point. The display of the photographs has been achieved by hiding or unhiding the respective level upon user input. A higher-order, persistent level contained the first-person actor at a fixed position, which corresponds to the backdrops' center point.

The graphical user interface (GUI) shown in Fig. 3 was implemented into the UE level to guide the participants through the experiment and facilitate the simultaneous comparison between the stimuli. The graphical user interface (GUI) provides buttons to select the stimulus/scene to explore perceive. The order in which the stimuli appeared was randomized across participants.

During the experiment's first phase, the GUI contained solely buttons with the numbers 1–8 for switching between stimuli. In phase three, the GUI provided sliders to enter ratings on a continuous rating scale (lower to higher anchor) and incorporated two extra buttons to change between the attributes. The participants used the paired wireless controllers to navigate through the GUI and enter their rating values.



(a) (b) (c)

FIG. 3. The listening test environments. (a) User interface in Unreal Engine for all participants. (b) Frontal view of the test room in Aachen, Germany. (c) Lateral view of the test room in Barcelona, Spain.

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E. Stimuli

The choice for the piece of music was Beethoven's symphony no. 7, movement 1, bars 14–16, which corresponds to a ca. 11 s excerpt. The piece was used as an anechoic recording, according to Pätynen *et al.* (2008b). In this recording, each orchestra instrument was recorded as an anechoic audio track. Then, each anechoic recording was convolved with the spatial IR between one loudspeaker and a receiver point. Each loudspeaker position substitutes a specific instrument's position on stage. Thus, the sum of all loudspeaker signals convolved with their respective anechoic input signal yields the final stimulus at a receiver location.

In order to render plausible and well-externalized acoustic virtual environments, all sound sources were calibrated by applying the source power calibration method. All IRs were recorded in absolute referenced values, and all anechoic audio tracks from different instruments were recorded with the same calibrated microphone levels. In this way, the convolutions of the IRs with their corresponding anechoic instruments were all relatively calibrated.

The reproduction chain consisted of a Focusrite Scarlett 4i4 4th audio interface (Focusrite Audio Engineering Ltd., High Wycombe, Buckinghamshire, United Kingdom) and a pair of Sennheiser HD650 open-back headphones. A general equalization and headphone transfer function compensation measured once for the HD650 was used for all participants in both laboratories (Schmitz, 1995). To determine a suitable gain leading to a convincing overall reproduction, the ear canal SPL created by the headphones was used as a metric. To measure this, a GRAS 45CA (Gras Acoustics, Holte, Denmark) headphone test fixture with two ear canal simulators was used in combination with a second audio interface (Focusrite Scarlett i2i, Focusrite Plc, High Wycombe, Buckinghamshire, UK). The analog-to-digital (A/D) converter built into the interface was calibrated using a sine generator and the microphone sensitivities of the test fixture were included. The authors placed the headphones on the test fixture and auralized a signal with a target SPL from the previous calibration step. The gain for the reproduction interface was adjusted until that level was reached. Thereby, it was ensured that the reproduction of the calibrated virtual acoustic environment was realistic in volume. The same fixed calibration settings, headphones, and audio interfaces were used in one laboratory and translated into the other laboratory, in a way that the reproduction levels between both laboratories could be the same.

The decoding of the Ambisonics audio files into the binaural down mix was performed in virtual acoustics (VA) (Institute for Hearing Technology and Acoustics, RWTH Aachen University *et al.*, 2022). The software incorporates dynamic head movements that are tracked by HMD. VA and UE are synchronized via sharing the location and orientation of the receiver/rendering point, with the Unreal VA Plugin (Unreal Virtual Acoustics Plugin, RWTH Aachen University, VR Group).

F. Participants

In the current study, we tried to search two groups of participants able to represent the aimed educational background differences:

- Architects (AR): a group of 20 students and staff of the Barcelona School of Architecture, Universitat Politècnica de Catalunya, with background and interest in concert halls. The participant age ranges between 19 and 46 yrs of age. A total of 40% of the participants were female. The data were collected between September 2023 and March 2024.
- Acousticians (AC): a group of 23 students, staff, and visitors of the Institute for Hearing Technology and Acoustics, RWTH Aachen University, with background and interest in concert halls. The participant age ranges between 20 and 33 yrs old. A total of 45% of the participants were female. The data were collected between October 2022 and February 2023. These data were previously presented in Heck *et al.* (2025).

No participant took part in both experiments; hence, allowing for just comparisons between groups. In particular, every participant assessed the scenes with equal experimental conditions, namely GUIs, HMD, and headphones.

Although the participants cannot be considered as expert assessors, most of them are students or staff with experience in visuals and acoustics-related fields, respectively. None of the participants reported hearing loss, which made all of their results eligible for subsequent analysis.

The experiment consists of eight stimuli, corresponding to two listener positions for each of the four selected halls. After listening to the excerpt, participants are asked to describe the space, regarding the visual and auditory aspects, with a *descriptor* and rating each stimuli on a scale from minimum to maximum, as it is shown in Fig. 3 and further described in Sec. III G. The data are hence anonymised for the consequent analysis in this paper.)

G. Experimental procedure

The experiment followed a procedure that is known as IVP. The technique has been developed from the so-called Flash profile and has been applied to concert hall evaluation (Lokki *et al.*, 2011; Lokki *et al.*, 2016) previously. The scope of this method is to collect attributes that describe differences between stimulus-perceived music in concert halls, for example. Those attributes are clustered and, after a hierarchical multiple factorial analysis (HMFA), the main attribute dimensions given by the participants are found. The method is usually used as an exploratory inquiry to unveil the most used and distinguished attributes. In this paper, it consisted of the following elements:

- introduction to the experiment and demographics questionnaire,
- first phase of the experiment consisting of the stimuli exploration in VR and development of an individual vocabulary list,
- second phase to review and revise the vocabulary list,

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- third phase, where the items from the vocabulary list are used as attributes to assess the stimuli, and
- a short subsequent questionnaire to inquire about supplementary information.

During the experiment's first phase, the participants were asked to explore the eight audio-visual scenes, each corresponding to one of the receiver locations introduced in Fig. 1. While exploring the scenes, each participant was asked to find four to six attributes (i.e., individual vocabulary) that can be used to describe and distinguish the scenes by auditory and visual means, respectively. An attribute defined a perceptual dimension to assess the scenes. For each attribute, a lower and a higher anchor were to be defined to facilitate the assessment/rating in phase 3.

The second phase was used to review the collected vocabulary list, together with the experimenter, to ensure that the output list of attributes was concise.

In the third phase, the participants again navigated through the different scenes. They were asked to assess the differences by entering their ratings on a *multiple stimuli with hidden reference and anchor (MUSHRA)-like interface* (Fig. 3). The interface allowed participants to switch between different listening locations/concert hall positions, while the music was continuously looped. The attributes were assessed successively. The participants could decide to terminate the experiment or to reassess the attributes, when all attributes and scenes were assessed. The number of stimuli was determined with the aim of ensuring that they can be processed reasonably within a MUSHRA-like interface, following previous similar research designs (Lokki *et al.*, 2011; Lokki *et al.*,2012).

IV. METHODS

In order to investigate the differences between the attributes used by architects and acousticians, a series of analysis in a hierarchical structure was conducted, as shown in Fig. 4: a statistical distribution analysis at the attributes level (bottom level); two consecutive multiple factorial analyses (MFA) at the group level (architects and acousticians), and at the modality levels (auditory and visual); and finally, a HMFA of the complete attribute dataset. It is worth noting the analysis at each different level has been performed separately for auditory and for visual attributes; except for the final HMFA level, where the whole dataset was considered.

First, a statistical distribution analysis provided as a result an overview of the spread of the attributes used by architects and acousticians. Visual and auditory attributes were clustered according to previous literature by Key and Gross (2021) and Kuusinen and Lokki (2017), respectively. Based on these clusters, the number and distribution of attributes were compared.

Second, MFAs at the group level were performed. In order to achieve this, a principal components analysis (PCA) per assessor has been performed to output a separate matrix per assessor. These matrices have been the input for the MFA at the group levels and several PCAs were conducted for specific groups of assessors (architects and acousticians) in order to reveal which main dimensions describe the distribution of attributes within the architects and within the acousticians groups. The first three MFA dimensions were selected for each of the analysis since they explain at least 70% of the variability in all MFA analyses. Two-dimensional (2D) plots representing data on dimensions 1 and 2 are created representing vectors for each of the attribute clusters. The angle of vectors indicates the correlation between respective variables, and the length of the vectors indicate the correlation coefficient of the respective dimensions.

Third, MFAs analysis at the modality level was used to quantify the differences between architects and acousticians in using auditory and visual attributes. For this purpose, distribution ellipses were used to represent the different clusters (Zubin, 1938). Given an attribute X, a cluster of X could be formed by "drawing" an ellipsis enclosure around the descriptor samples. The clusters were visualized by projecting the samples and enclosures onto the MFA space. Based on the ellipsis representation, similarity and difference between clustered attributes were quantified. For this purpose, two metrics were used:

- *Euler distance* (Cohen, 2004) between centroids of the clusters. This aims to quantify how much, in the panel average, differently the given attribute is used and correlated to the principle perception components. Let

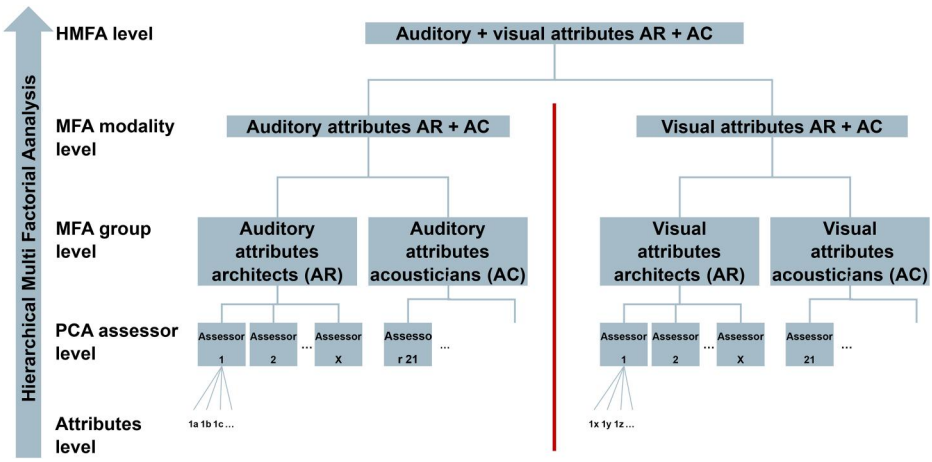

FIG. 4. Organization of the data for the HMFH, with the (a) five hierarchical levels.

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$x = (x_1, x_2), y = (y_1, y_2) \in R^2$ be the centroids of cluster X and Y, respectively. We define

$$\text{EulerDistance}(X, Y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2}.$$

The closer the Euler distance, the closer the centroids between AC and AR are located.

- *Jaccard similarity* (Murphy, 1996), to qualify the overlap between the elliptical enclosures of the clusters. If we define $\hat{X}$ as the enclosure of cluster X,

$$\text{JaccardSimilarity}(X, Y) = \frac{\hat{X} \cap \hat{Y}}{\hat{X} \cup \hat{Y}}.$$

The higher the Jaccard similarity measure, the more the elliptical enclosures between AC and AR overlap.

Fourth, the HMFA at the highest level combined all data in the same analysis at the modality level (auditory and visual), conducted for the auditory and visual attributes, respectively, including both architects and acousticians data and the objective RA. For this purpose, superimposed representations at the HMFA level of the concert hall receiver positions were performed following the existing literature (Lokki *et al.*, 2011) and distance comparisons between cluster centroids at the HMFA level were used to quantify the consensus across perceptual dimensions across architects and acousticians (Figs. 5 and 6).

V. RESULTS

A. MFA at the architects and acousticians' level

Figures 7 and 8 show the multiple factorial analysis (MFA) performed for each of the participants' group (AC, AR) for the auditory and visual modalities, respectively. Both architects' and acousticians' responses can be observed and compared among them between the left and the right plots, since both have been represented in the same MFA dimensional space. The X and Y dimensions of each MFA correspond to dimensions 1 and 2, with varying variances for each: dimensions 1 and 2 explain the total of 69.79% of

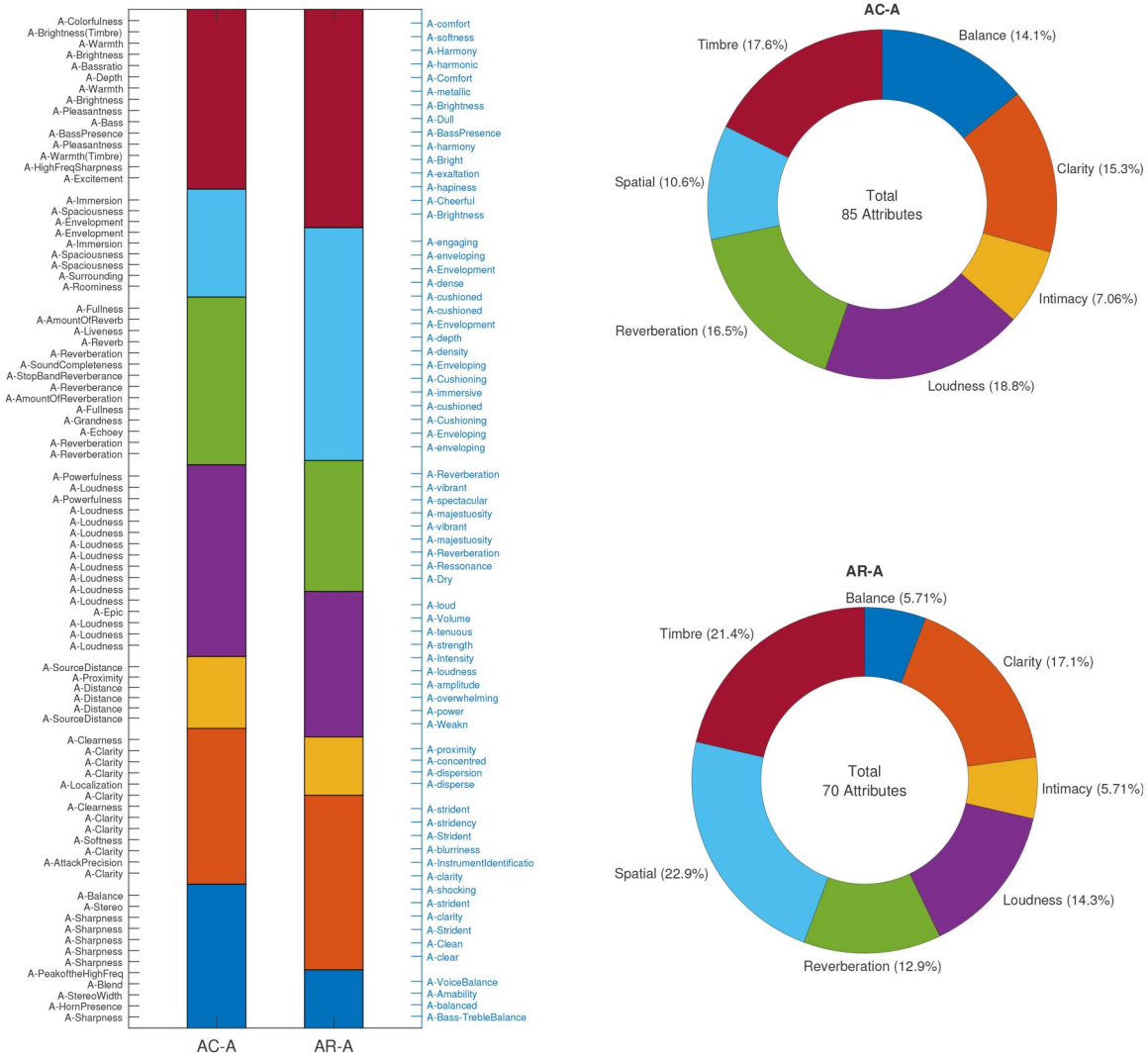

FIG. 5. The collected auditory attributes clustered according to Kuusinen and Lokki (2017).

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the data variance for the auditory attributes; and the total of 62.23% of the data variance for the visual attributes.

Regarding the auditory attributes (Fig. 7), it is worth noting that architects [Fig. 7(b)] use a more spread distribution of the perceptual space than acousticians [Fig. 7(a)]. We can see that architects use five different dimensions to describe auditory aspects (balance, intimacy, timbre-spatial, reverberation, and loudness-clarity), whereas acousticians use a two-dimensional space (loudness-clarity-balance-reverberation vs timbre-spatial-intimacy).

Regarding the visual attributes, we can see a rather opposite effect (Fig. 8). Here, acousticians [Fig. 8(a)] use a more spread distribution of the perceptual space than architects [Fig. 8(b)]. We can see that architects use three different dimensions whereas acousticians distinguish five different dimensions spread through the 180° of the perceptual space.

B. Cluster (dis)similarities at the MFA architects and acousticians level

Table I shows the results of the similarity comparisons between the cluster pairs among participant groups using the ellipses metrics described above. The comparison was performed at the MFA modalities level (see Fig. 4), merging the architects' and acousticians' data for two HMFA separate datasets: one for auditory and another for visual attributes.

If we take a closer look at the Euler distance between the architects' and acousticians' clusters, the auditory clusters (Table I) loudness and spatial present the smallest values (0,097 and 0,297, in dimensions 1 and 2), thus providing that the centroids between the AC and AR are very close. This reveals that there is a relative high agreement between AC and AR on what loudness and spatial clusters represent, but less agreement on other clusters, such as balance, intimacy, and reverberation. This is supported also by the Jaccard similarity values, which is the highest high at loudness and spatial but lower in the other clusters. A similar result can be extracted from the visual clusters (Table I). There, the clusters' geometric, light, color, and feelings present the biggest consensus, revealing that there is a relative high agreement between AC and AR in those clusters, but a rather lower agreement between both groups in the cluster called balance.

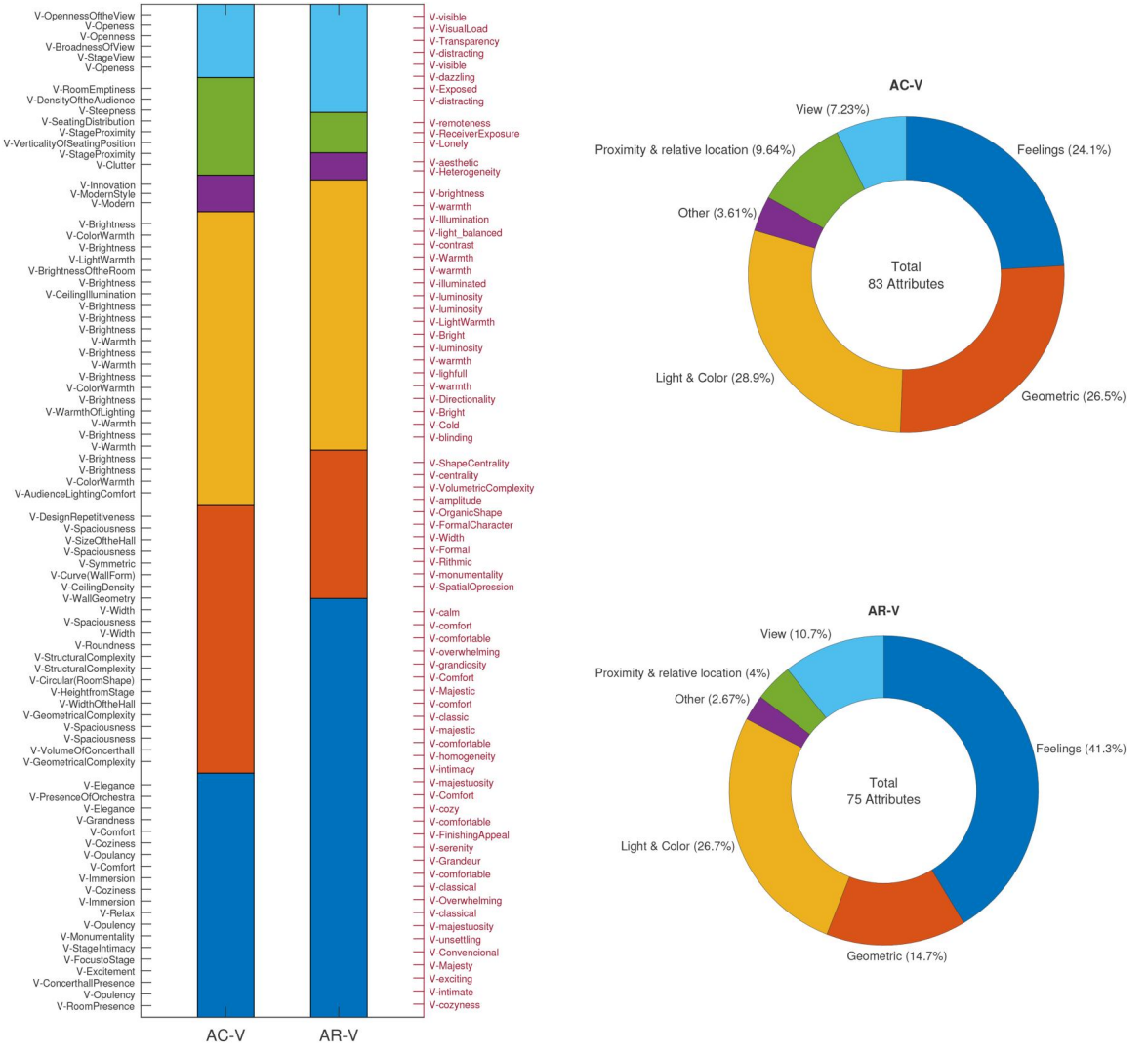

FIG. 6. The collected visual attributes clustered according to Key and Gross (2021).

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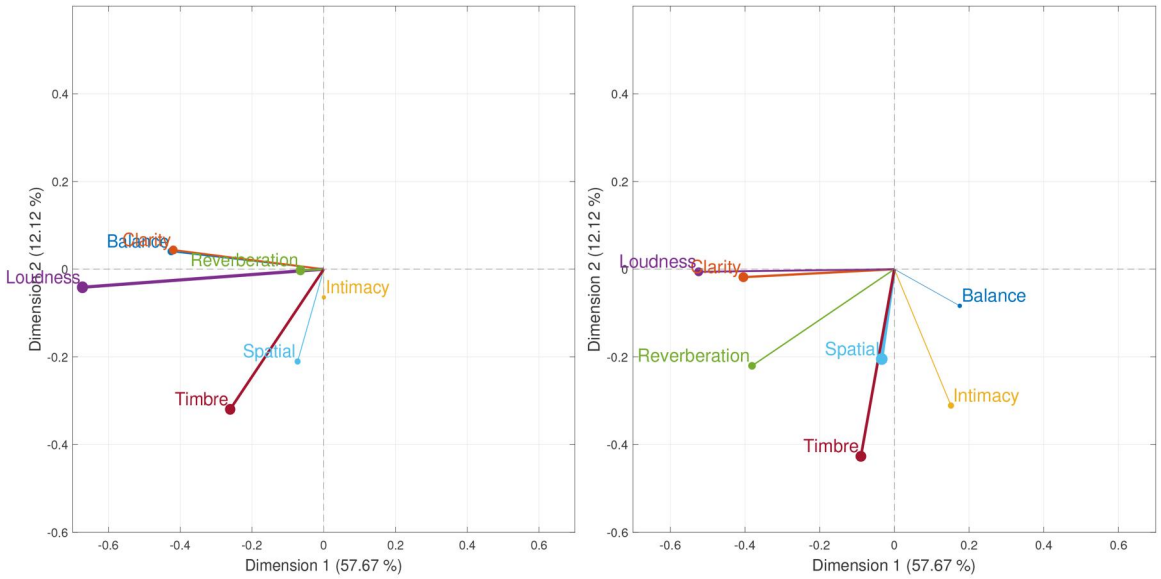

FIG. 7. Auditory attribute clusters represented through the common two-dimensional MFA space of acousticians and architects together. (a) Only the acousticians' data are represented (AC-A) and (b) only the architects' data are represented (AR-A).

C. Superposition of concert halls at the MFA modality levels

Without moving further from the achieved MFA modality level, Figs. 9(a) and 10(a) represent the concert halls and their examined receiver seats ranked according to the auditory and visual modalities, respectively. Complementary Figs. 10(a) and 10(b) show the vector representations of the corresponding perceptual dimensions. In this way, a direct comparison between the concert halls [Fig. 10(a)] and their corresponding perceptual dimensions [Fig. 10(b)] can be established.

D. Comparison of subjective attributes with room acoustical parameters

Arriving to the highest HMFA level allows us to compare auditory subjective and objective RA in common dimensions. Figures 11(a) and 11(b) show this representation. In Fig. 11(a), the superimposed representation shows all concert halls positions represented by their RA and their subjective auditory parameters, divided by architects (AR) and acousticians (AC). This plot shows how strong the correlation coefficients are between the subjective and the objective parameters for each concert hall position. In

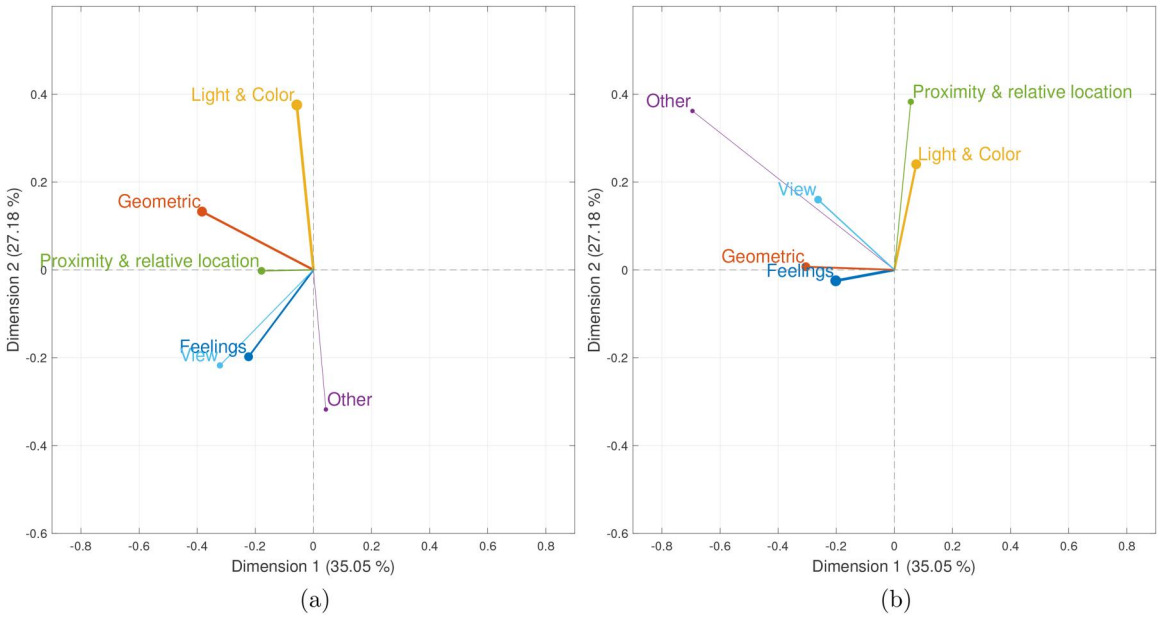

FIG. 8. Visual attribute clusters represented through the common two-dimensional MFA space of acousticians and architects together. (a) Only the acousticians' data are represented (AC-V) and (b) only the architects' data are represented (AR-V).

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TABLE I. (Dis)similarity metrics between panels (AC vs AR) for individual attributes. The highest value for JS and the lowest value of ED for each attribute cluster has been marked in bold, for both auditory (A) and visual (V). This selection has been performed in dimensions 1 and 2, since they represent the highest variance of the data. JS, Jaccard similarity; ED, Euler distance.

Dimensions	Attribute cluster	JS	ED
1-2	A-Balance	0.178	0.711
1-2	A-Clarity	0.482	0.141
1-2	A-Intimacy	0.331	0.5289
1-2	A-Loudness	0.186	0.194
1-2	A-Reverberation	0.287	0.460
1-2	A-Spatial	**0.626**	**0.079**
1-2	A-Timbre	0.510	0.284
1-2	V-Feelings	**0.653**	**0.195**
1-2	V-Geometric	**0.661**	**0.104**
1-2	V-Light & Color	**0.718**	**0.183**
1-2	V-Proximity & relative location	0.092	0.451
1-2	V-View	0.459	0.382
1-3	A-Balance	0.133	0.796
1-3	A-Clarity	0.635	0.199
1-3	A-Intimacy	0.504	0.310
1-3	A-Loudness	0.158	0.157
1-3	A-Reverberation	0.539	0.529
1-3	A-Spatial	**0.768**	**0.059**
1-3	A-Timbre	0.598	0.379
1-3	V-Feelings	0.641	0.089
1-3	V-Geometric	0.826	0.086
1-3	V-Light & Color	0.590	0.238
1-3	V-Proximity & relative location	0.168	0.272
1-3	V-View	0.459	0.231
2-3	A-Balance	0.552	0.375
2-3	A-Clarity	0.604	0.228
2-3	A-Intimacy	0.364	0.366
2-3	A-Loudness	0.384	0.129
2-3	A-Reverberation	0.384	0.532
2-3	A-Spatial	**0.578**	**0.080**
2-3	A-Timbre	0.709	0.257
2-3	V-Feelings	0.638	0.214
2-3	V-Geometric	0.798	0.134
2-3	V-Light & Color	0.601	0.238
2-3	V-Proximity & relative location	0.299	0.408
2-3	V-View	0.325	0.439

Fig. 11(b), the variables plot shows all subjective and objective parameters represented in the same dimensional space. Shown in brown, we can see the objective RA, whereas other colors represent the subjective attribute clusters. Here, it is possible to find each specific RA together with each subjective auditory parameter. The closer their centroids, the stronger the correlation coefficient present. Again, it is possible to distinguish the subjective attributes elicited by architects (AR-) and by acousticians (AC-). This representation shows whether both expert groups have a consensus between subjective and objective parameters.

VI. DISCUSSION

A. Visual descriptors

The visual descriptors were clustered according to the existing literature by Key and Gross (2021). Figure 6 shows the attributes and their clusters. The authors used the suggested number and name of clusters and grouped the given attributes accordingly. We also note that participants from both panels used a non-negligible portion of visual descriptors that is related to light and color (26.7%). Although these descriptors were previously not categorized as a single separate cluster (Key and Gross, 2021), in this study, we grouped these descriptors into an additional *Light & Color* cluster, to retain and investigate its statistical significance.

Next, we found that the two panels do not share the same groups of visual descriptors. For a total of 11 categories, including those from Key and Gross (2021) and the *Light & Color* category, the visual descriptors from AR span nine groups, while the AC panel used visual descriptors from seven groups. The AR refrain from using *Distance* and *Enclosure* descriptors, while the AC did not talk about *Enclosure*, *Movement*, *Privacy*, and *Territory*.

Feelings constitutes a large portion of the AR panel's visual perception (41.3%), whilst AC panel is slightly more balanced across groups, with *Light & Color* as the majority (28.9%). In both AC and AR, there are three main clusters, which contain around the 80% of the attributes, namely *Feelings*, *Geometric*, and *Light & Color*. However, it is worth noting that AC use a balanced proportion of all three clusters (24%, 26%, and 28%, respectively), whereas AC elicits a bigger use of *Feelings* (41%), and lower use of *Geometric* attributes (14%). This suggests that AC use more technical attributes to visually describe the rooms, and AR prefer describing the rooms visually using words that describe their perception.

B. Auditory descriptors

In terms of auditory descriptors, AR and AC panels share similar percentage ratios in average, with some exceptions (Fig. 5). First, *Intimacy* is ranked last among both panels. Second, the *Balance*-related attributes show less percentage ratios used by architects (5.71%) compared to acousticians (14.1%). The opposite effect can be observed for the *Spatial*-related attributes, where acousticians use 10% and architects use 22.9%. Finally, we can see also a notable difference: the AC panel has a relatively balanced use of descriptors, whilst the AR panel predominantly perceive spaces by *Timbre* or *Spatial* (44.3%).

C. Correlations between attributes and concert halls

Regarding how individual attributes correlate to concert hall perceptions, we observe that the visual perception of the AR panel is quasi-bidimensional [Fig. 8(b)]—it can be qualified by *Geometry* and *Feelings* in dimension 1 and *Light & Color, Proximity and Relative location* in the second dimension. The AC panel, on the contrary, shows a quite dispersed visual clusters distribution [Fig. 8(a)]—the clusters *Light &*

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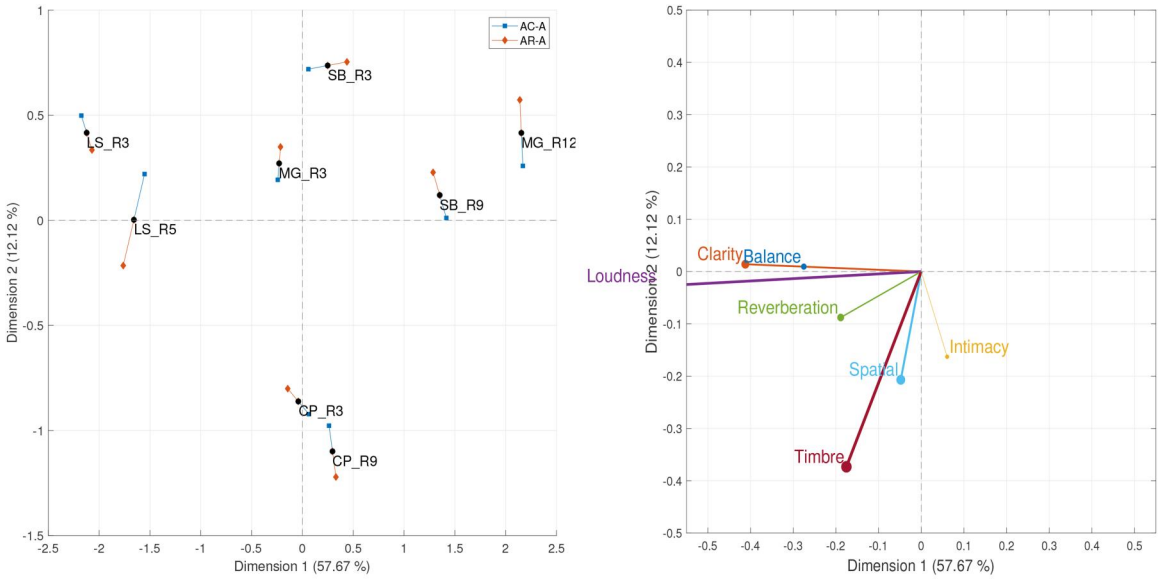


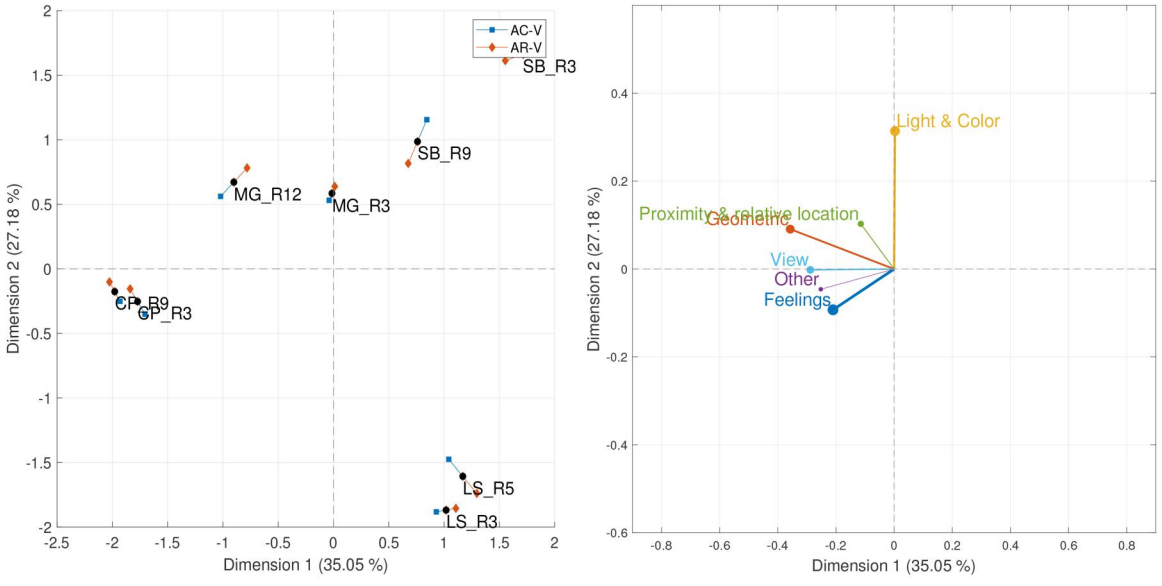
(a) (b)

FIG. 9. Auditory subjective data: superimposed (concert hall positions) and variables (attribute clusters) plots. Data are represented over the common MFA dimensional space of combined architects' and acousticians' data: (a) superimposed for AC and AR separately and (b) variables for combined AC and AR.

Color and *Proximity & Relative location* are placed in dimensions 1 and 2, respectively, and cluster *Feelings* and *Geometric* occupy the 45° axis. This distinction of both AR and AC groups demonstrates how AR visually perceive the concert halls with a bidimensional nature compared with the bidimensional nature of AC.

In the field of auditory attributes, the inverse effect can be observed. The auditory perception of the AC panel is quasi-bidimensional [Fig. 7(b)]—it can be qualified by *Balance*, *Reverberation*, and *Spatial* in dimension 1 and by *Loudness*, *Intimacy*, *Timbre*, and *Clarity* in a −45° axis. On the contrary, the AR panel shows a quite dispersed auditory clusters distribution [Fig. 7(a)]. Here, a different dimension appears every 45° of the dimensional space, from the very left with *Loudness and Clarity*, until almost 180° in the opposite direction with *Balance*, including *Reverberation*, *Timbre*, *Spatial*, and *Intimacy*. In total, five differentiable dimensions describe the auditory perceptual space of architects.

From these facts, it is worth noting that each AC and AR panel shows a quasi-bidimensional perception space for the modality in which participants have received more



(a) (b)

FIG. 10. Visual subjective data: superimposed (concert hall positions) and variables (attribute clusters) plots. Data are represented over the common MFA dimensional space of combined architects' and acousticians' data: (a) superimposed for AC and AR separately and (b) variables for combined AC and AR.

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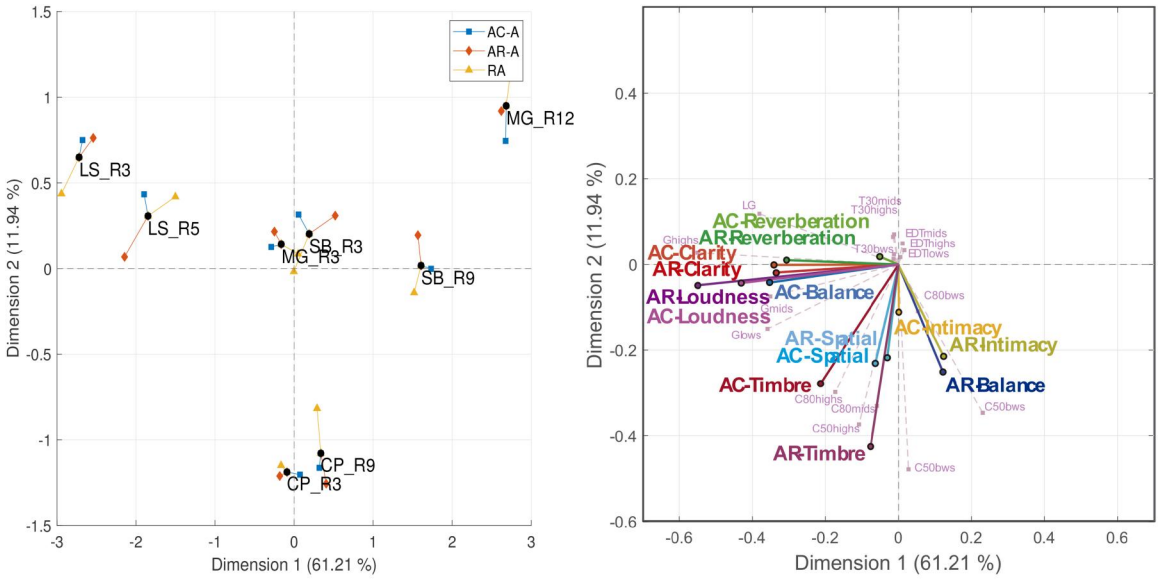

FIG. 11. Auditory subjective and objective RA: superimposed (concert hall positions) and variables (attribute clusters) plots. Data are represented over the common HMFA dimensional space of combined architects', acousticians', and RA's data: (a) superimposed and (b) variables.

training—namely, architects with visual and acousticians with auditory attributes—and a much more dispersed clusters distribution for the modality they are not used to.

D. Clustered attributes

In general, the smaller the centroid distance and the higher the Jaccard similarity, the more consistent the panels for the given attribute. We observe from Table I that for most of the listed attributes, there is a good consistency between panels (Jaccard similarity > 0.5, Euler distance ≤ 0.4). There are some attributes which the panels could not agree on, for example, *Auditory Balance* and *Visual View*, which is close in terms of centroid yet dissimilar in terms of overlapping. This hints that the variety of the descriptor usage is different between acoustician and architects in these areas.

E. Comparison of concert halls and listening positions

From Fig. 9, CP and LS have shown a strong consistency between listener positions; these positions are perceived as "close to each other" on the represented dimensions. On the contrary, changing the listener position in MG and SB could greatly influence the visual and auditory perception. Specifically for auditory perception, the AR and AC panels mainly disagree along dimension 2.

The analysis of the visual data in Fig. 10 reveals that the subjective visual data are mainly explained by the first dimension, which consists of attributes related to *Feelings, View*, and *Other* (styles), with the exception of the LS room, which differentiates from all the other rooms in perceptual attributes related to *Proximity & relative location* and *Light & Color*. This result suggests that the visual differences among rooms were explained by the change of view attributes (such as openness, broadness, exposure of stage, etc.) and personal feelings (such as elegance, majestic, or overwhelming, among others). Additionally, it also reveals that the subjective auditory data are mainly explained by the first dimensions, which consist of attributes related to *Loudness and Reverberation*, confirming previous literature by Lokki *et al.* (2012), with the exception of the CP room, which differentiates from all the others in perceptual attributes related to *Balance* and *Timbre*. This result suggests that the auditory differences among rooms can be mainly explained by the change of loudness and reverberation attributes (such as reverberance, strength, fullness, or stridency).

In addition, an intra-room analysis also suggests interesting insights. First, the subjective visual differences among the frontal and the rear seating position for each room (Fig. 10) are mainly explained by the dimensional axis of attributes related to *Geometry* for the CP and MG rooms and by attributes related to *Light & Color* for the SB and LS rooms (Fig. 10). These results suggest that the visual differences among seating positions are room dependent: CP and MG present significant geometrical variations, whereas SB and LS present light and color variations. When we consider the subjective auditory differences among frontal and rear seating positions (Fig. 9), we observe that they are mainly explained by the second dimension, which consists of attributes related to *Balance and Timbre* (Fig. 9), with the exception of the MG room, which is explained by attributes related to *Loudness and Reverberation*. These results suggest that the auditory differences among seating positions can be explained better with differences in terms of timbre and balance differences (such as softness, warmth, clarity, colorfulness, or attack precision).

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Finally, the analysis between the subjective and objective parameters shown at Fig. 11 reveals an interesting aspect. Every subjective auditory attribute cluster correlates most with expected objective RA. In particular, AC and AR expert groups coincide on most of the correlations: subjective loudness (for both AC and AR groups) correlates with strength *G* mids and *G* highs; subjective intimacy correlates with C50 mids and C50 lows; subjective timber and spatial correlates in a weak way with *C*80 highs and *C*80 mids. However, there is one subjective parameter for which there is clearly no consensus between AR and AC: subjective balance. For the AR subjective balance correlates with *C*50 lows, whereas for the AC, it correlates with *G* mids. This poses the interesting distinction and might be worth noticing whenever there are shared discussions on perceived balance among both expert groups.

VII. CONCLUSION AND OUTLOOK

The presented study applied the IVP technique to assess four concert halls by evaluations of AC and AR panels. Respectively, two sets of vocabulary have been collected. The main difference between both vocabulary lists was found in the categories *Distance*, *Movement*, *Privacy*, and *Territory*. The main conclusions found are:

First, the architects panel used predominantly visual *Feelings* and auditory *Timbre and Spatial* descriptors, whilst the acoustician panel has a relatively balanced use of perceptual descriptors (Figs. 5 and 6).

Second, using cluster similarity methods, we are able to observe and quantify the descriptor consistencies between AR and AC panels. The method shows promising results in identifying high consistencies in auditory *Balance* and visual *View*, but significant discrepancies in using auditory *Balance* and *Intimacy*.

Third, the results suggest that architects and acousticians show a quasi-bidimensional perception space for the modality they are more trained with—namely architects with visual and acousticians with auditory attributes—and a much more dispersed clusters distribution for the modality they are not used to using.

Fourth, the HMFA suggests that the auditory differences among concert halls can be mainly explained by the variations of loudness and reverberation, while the auditory differences among seating positions can be mainly explained by the timbre and balance variations. The same analysis also suggests that the visual differences among concert halls can be mainly explained by differences in view and perceived feelings, while the visual differences among seating positions can be explained by perceived geometrical and light variations.

Fifth, architects and acousticians present a consensus for most of the correlations between the subjective auditory attributes and objective RA, except for subjective balance. In this case, architects correlate with the clarity *C*50 parameter whereas acousticians correlate with the strength *G* parameter.

Finally, the study has been limited to only four concert halls with two receiver locations each. This and the choice of only one short music excerpt might be limitations to the study. Nevertheless, it was shown that the applied techniques are able to identify differences in auditory and visual evaluations of concert halls between architects and acousticians. Additionally, by comparing vocabularies from both groups, we have shown results for "Spanish architectural students" vs "German acoustics students." The authors are aware of many other factors that might differentiate them: language, nationality, cultural background, etc. However, finding the significance of the selected factors against other potential factors is outside of the scope of this study and might be a focus in further studies. The collection of more case-specific vocabulary for similar scenarios and more participants in more variety in cultural background could be ways to verify the approach's robustness. Finally, the authors recognize the opportunities given by the IVP method to bridge between qualitative and quantitative analysis. They hope the method will be tested in future experiments involving other experts and non-expert users of auditoriums, such as acoustic design experts, architects with auditorium design experience, or musicians. Nevertheless, they are also aware that other methods could be used to analyze the same dataset for answering various other research questions.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Ethics Approval

The research related to human use has complied with all the relevant national regulations, institutional policies, and in accordance with the tenets of the Helsinki Declaration. Informed consent has been obtained from all individuals included in this study. This research complied with the RWTH Aachen University Code of Ethics and was approved by the Institute for Hearing Technology and Acoustics at the same university on May 11, 2022.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Bech, S., and Zacharov, N. (**2007**). *Perceptual Audio Evaluation - Theory, Method and Application* (John Wiley & Sons, New York).

Chen, Y., and Cabrera, D. (**2021**). "The effect of concert hall color on preference and auditory perception," Appl. Acoust. **171**, 107544.

Chen, Y., Cabrera, D., and Alais, D. (**2023**). "Modelling audiovisual seat preference in virtual concert halls," Appl. Acoust. **212**, 109589.

Cohen, D. (**2004**). *Precalculus: A Problems-Oriented Approach* (Cengage Learning, Independence, KY).

Delarue, J., and Sieffermann, J.-M. (**2004**). "Sensory mapping using Flash profile. Comparison with a conventional descriptive method for the evaluation of the flavour of fruit dairy products," Food Qual. Prefer. **15**(4), 383–392.

Doeffinger, D. (**2009**). *Creative Shutter Speed: Master Your Camera's Most Powerful Control* (Wiley, Indianapolis).

Heck, J., Llorca-Bofí, J., Park, H., Meyer-Kahlen, N., Lokki, T., and Vorländer, M. (**2025**). "Comparison of the auditory and auditory-visual perception in four concert halls," Proc. Meet. Acoust. **58**(1), 015014.

Institute for Hearing Technology and Acoustics, RWTH Aachen University, Schäfer, P., Palenda, P., Aspöck, L., and Vorländer, M. (**2022**). "Virtual acoustics - A real-time auralization framework for scientific research" Zenodo. https://doi.org/10.5281/ZENODO.13744523 (Last viewed 15 August 2026).

Key, S., and Gross, M. (**2021**). "From architects' terms to computable descriptions of spatial qualities," Spat. Cogn. Comput. **21**(3), 173–196.

Kürer, R., Plenge, G., and Wilkens, H. (**1969**). "Correct spatial sound perception rendered by a special 2-channel recording method," https://www.semanticscholar.org/paper/Correct-Spatial-Sound-Perception-Rendered-by-a-K%C3%BCrer-Plenge/42841cd606dda7fac70d5640623ea9f78e00f802 (Last viewed 21 August 2026).

Kuusinen, A., and Lokki, T. (**2017**). "Wheel of concert hall acoustics," Acta. Acustica. **103**(2), 185–188.

Le Dien, S., and Pagès, J. (**2003**). "Hierarchical multiple factor analysis: Application to the comparison of sensory profiles," Food Qual. Prefer. **14**(5-6), 397–403.

Liu, X., Kang, J., Ma, H., and Wang, C. (**2021**). "Comparison between architects and non-architects on perceptions of architectural acoustic environments," Appl. Acoust. **184**, 108313.

Llorca-Bofí, J., Heck, J., Atay, G., López, D. I., and Vorlaender, M. (**2025**). "Muskla database - Muenchen, Stuttgart, Koeln and Lahti auditoriums narrow angle and spherical photographs for perceptual studies in architecture," [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.15920854 (Last viewed 15 August 2026).

Llorca-Bofí, J., Heck, J., and Vorländer, M. (**2023**). "Within-subject exploration of individual vocabulary profiles from urban soundscape variations," in *DAGA 2022-48, Jahrestagung für Akustik* (Deutsche Gesellschaft für Akustik, Hamburg, Germany).

Llorca-Bofí, J., Sezer, C., Heck, J., and Vorländer, M. (**2022**). "Unfolding urban vocabularies–audio-visual description of public spaces," in *DAGA 2022-48, Jahrestagung für Akustik* (Deutsche Gesellschaft für Akustik, Stuttgart, Germany).

Lokki, T., Pätynen, J., Kuusinen, A., and Tervo, S. (**2012**). "Disentangling preference ratings of concert hall acoustics using subjective sensory profiles," J. Acoust. Soc. Am. **132**(5), 3148–3161.

Lokki, T., Pätynen, J., Kuusinen, A., and Tervo, S. (**2016**). "Concert hall acoustics: Repertoire, listening position, and individual taste of the listeners influence the qualitative attributes and preferences," J. Acoust. Soc. Am. **140**(1), 551–562.

Lokki, T., Pätynen, J., Kuusinen, A., Vertanen, H., and Tervo, S. (**2011**). "Concert hall acoustics assessment with individually elicited attributes," J. Acoust. Soc. Am. **130**(2), 835–849.

Lorho, G. (**2007**). "Perceptual evaluation of mobile multimedia loudspeakers," https://www.semanticscholar.org/paper/Perceptual-Evaluation-of-Mobile-Multimedia-Lorho/20f478dde0c8aa09ed25426e469f3cb4aa7ac3da (Last viewed 21 August 2026).

Muckenhirn, A. (**2012**). "Architects and acousticians: Are they able to understand each other?," *Proceedings of the Acoustics 2012 Nantes Conference, Nantes, France*, pp. 3235–3238.

Murphy, A. H. (**1996**). "The Finley affair: A signal event in the history of forecast verification," Wea. Forecasting **11**(1), 3–20.

Naccari, F., Bruna, A., Capra, A., Castorina, A., and Cariolo, S. (**2005**). "Automatic image classification by color analysis," in *Proc. SPIE 5678, Digital Photography*, edited by N. Sampat, J. M. DiCarlo, and R. J. Motta (SPIE, Bellingham, WA), p. 129.

Neidhardt, A., Schneiderwind, C., and Klein, F. (**2022**). "Perceptual matching of room acoustics for auditory augmented reality in small rooms–literature review and theoretical framework," Trends Hear. **26**, 23312165221092919.

Oskam, T., Hornung, A., Sumner, R. W., and Gross, M. (**2012**). "Fast and stable color balancing for images and augmented reality," in *2012 Second International Conference on 3D Imaging, Modeling, Processing, Visualization & Transmission*, Zurich, Switzerland (IEEE Computer Society, Washington, DC), pp. 49–56.

Ottley, M., and Chen, Y. (**2024**). "Use of virtual reality and auralization as a training tool for acoustic practitioners," Proc. Meet. Acoust. **52**(1), 015003.

Pätynen, J., Pulkki, V., and Lokki, T. (**2008a**). "Anechoic recording system for symphony orchestra," Acta Acust. united Acust. **94**(6), 856–865.

Pätynen, J., Tervo, S., and Lokki, T. (**2008b**). "A loudspeaker orchestra for concert hall studies," in *The Seventh International Conference on Auditorium Acoustics*, Oslo, Norway, 3.-5.10. 2008, Institute of Acoustics, pp. 45–52.

Reinhard, E., Adhikhmin, M., Gooch, B., and Shirley, P. (**2001**). "Color transfer between images," IEEE Comput. Graph. Appl. **21**(5), 34–41.

Rindel, J. H., Otondo, F., and Christensen, C. L. (**2004**). "Sound source representation for auralization," https://api.semanticscholar.org/CorpusID:49569458 (Last viewed 15 August 2026).

Schmitz, A. (**1995**). "Ein neues digitales Kunstkopfmeßsystem" ("A new digital artificial head measurement system"), Acustica: International Journal on Acoustics **81**(4), 416–420. https://publications.rwth-aachen.de/record/136631 (Last viewed 15 August 2026).

Schroeder, M. R., Gottlob, D., and Siebrasse, K. F. (**1974**). "Comparative study of European concert halls: Correlation of subjective preference with geometric and acoustic parameters," J. Acoust. Soc. Am. **56**(4), 1195–1201.

Soulodre, G. A., and Bradley, J. S. (**1995**). "Subjective evaluation of new room acoustic measures," J. Acoust. Soc. Am. **98**(1), 294–301.

Tervo, S., Pätynen, J., Kuusinen, A., and Lokki, T. (**2013**). "Spatial decomposition method for room impulse responses," J. Audio Eng. Soc. **61**, 16–27.

Thomson, D. M. H., and McEwan, J. A. (**1988**). "An application of the repertory grid method to investigate consumer perceptions of foods," Appetite **10**(3), 181–193.

Weinzierl, S., Lepa, S., and Ackermann, D. (**2018**). "A measuring instrument for the auditory perception of rooms: The Room Acoustical Quality Inventory (RAQI)," J. Acoust. Soc. Am. **144**(3), 1245–1257.

Williams, A. A., and Arnold, G. M. (**1985**). "A comparison of the aromas of six coffees characterised by conventional profiling, free-choice profiling and similarity scaling methods," J. Sci. Food Agric. **36**(3), 204–214.

Williams, A. A., and Langron, S. P. (**1984**). "The use of free-choice profiling for the evaluation of commercial ports," J. Sci. Food Agric. **35**(5), 558–568.

Zubin, J. (**1938**). "A technique for measuring like-mindedness," J. Abnorm. Soc. Psychol. **33**(4), 508–516.

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