

SUBJECTIVE EVALUATION BETWEEN MEASURED AND SIMULATED AURALIZATIONS IN BRAS' ROOM 11 ACCORDING TO SAQI CRITERIA

AVALIAÇÃO SUBJETIVA COMPARATIVA ENTRE AURALIZAÇÕES MEDIDAS E
SIMULADAS NA SALA 11 DO BRAS SEGUNDO CRITÉRIOS SAQI

EVALUACIÓN SUBJETIVA COMPARATIVA ENTRE AURALIZACIONES
MEDIDAS Y SIMULADAS EN LA SALA 11 DEL BRAS SEGÚN CRITERIOS SAQI

Gabriel Braga Regattieri Sampaio¹, Viviane Suzey Gomes de Melo², Roberto Aizik Tenenbaum³

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ABSTRACT

Acoustic virtual reality is a concept well explored by room acoustics software, mainly for listening to an environment prior to build it. The technique used for this purpose is the auralization, which can be done using simulated or measured binaural impulse responses (BRIRs), and the software reliability depends on how close are the signals. The paper deals with subjective tests involving the two kinds of spatial audio. The research aims to verify how close to measurements a particular room acoustic simulation software from the perceptual listening point, using parameters from the Spatial Audio Quality Inventory (SAQI). The simulated and measured BRIRs in Scene 11 of the Benchmark for Room Acoustics Simulation (BRAS) with 5 types of distinct sound signals, and the resulting auralizations were used in subjective tests involving 10 SAQI parameters and 26 volunteers to assess the quality of the spatial signals. The volunteers' perception diverged when comparing the measured and simulated auralizations for cases involving parameters from the timbre category and converged for cases from the geometry, room, dynamic and general categories of SAQI. Furthermore, the software auralizations were considered as plausible, not showing any artifacts, but they can not be taken as fully authentic, since that some differences were perceived.

Keywords: Room Acoustics Simulation. Auralization. SAQI. Perceptual Tests. Spatial Acoustic Quality.

RESUMO

A realidade virtual acústica é um conceito amplamente explorado por softwares de acústica de salas, principalmente para audição prévia de um ambiente antes de sua construção. A técnica utilizada para este propósito é a aurilização, que pode ser realizada usando respostas impulsivas

¹Master's Student in Acoustic Engineering, Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brazil. E-mail: gabriel.sampaio@eac.ufsm.br Orcid: <https://orcid.org/0000-0001-7645-9430>

²Ph.D in Architect, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Rio de Janeiro, Brazil. E-mail: viviane.melo@ufsm.br Orcid: <https://orcid.org/0000-0002-2354-6167>

³Ph.D in Mechanical Engineer, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Rio de Janeiro, Brazil. E-mail: ratenenbaum@gmail.com Orcid: <https://orcid.org/0000-0002-5268-3849>

biauriculares (BRIRs), simuladas ou medidas, e a confiabilidade do software depende de quão próximos são os sinais. O artigo trata de testes subjetivos envolvendo os dois tipos de áudio espacial. A pesquisa visa verificar quão próximas das medições uma simulação acústica de sala particular está do ponto de vista da audição perceptual, usando parâmetros do Inventário de Qualidade de Áudio Espacial (SAQI). As BRIRs simuladas e medidas na Cena 11 do Benchmark for Room Acoustics Simulation (BRAS) com cinco tipos de sinais sonoros distintos, e as aurilizações resultantes foram usadas em testes subjetivos envolvendo dez parâmetros do SAQI e 26 voluntários para avaliar a qualidade dos sinais espaciais. A percepção dos voluntários divergiu ao comparar as aurilizações medidas e simuladas para casos envolvendo parâmetros da categoria timbre e convergiu para casos das categorias geometria, sala, dinâmica e geral do SAQI. Além disso, as aurilizações do software foram consideradas plausíveis, não apresentando artefatos, mas não podem ser tomadas como plenamente autênticas, uma vez que algumas diferenças foram percebidas.

Palavras-chave: Simulação de Acústica de Salas. Aurilização. SAQI. Testes Perceptuais. Qualidade Acústica Espacial.

RESUMEN

La realidad virtual acústica es un concepto ampliamente explorado por programas de acústica de salas, principalmente para la audición previa de un ambiente antes de su construcción. La técnica utilizada para este propósito es la auralización, que puede realizarse utilizando respuestas impulsivas binaurales (BRIRs) simuladas o medidas, y la fiabilidad del software depende de cuán próximas sean las señales. El artículo trata sobre pruebas subjetivas que involucran los dos tipos de audio espacial. La investigación busca verificar cuán cerca de las mediciones se encuentra un software particular de simulación acústica de salas desde el punto de vista de la audición perceptual, utilizando parámetros del Inventario de Calidad de Audio Espacial (SAQI). Las BRIRs simuladas y medidas en la Escena 11 del Benchmark for Room Acoustics Simulation (BRAS), con cinco tipos de señales sonoras distintas, y las auralizaciones resultantes se utilizaron en pruebas subjetivas con diez parámetros SAQI y 26 voluntarios para evaluar la calidad de las señales espaciales. La percepción de los voluntarios divergió al comparar las auralizaciones medidas y simuladas para los casos que involucraban parámetros de la categoría timbre, y convergió para los casos de las categorías geometría, sala, dinámica y general del SAQI. Además, las auralizaciones del software fueron consideradas plausibles, sin presentar artefactos, pero no pueden considerarse completamente auténticas, ya que se percibieron algunas diferencias.

Palabras clave: Simulación de Acústica de Salas. Auralización. SAQI. Pruebas Perceptuales. Calidad Acústica Espacial.



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INTRODUCTION

Acoustic virtual reality (AVR) is a concept that has been widely explored by room acoustics software, mainly to listen to the sound in an environment before it is built, or even to represent the acoustics of an existing one. This is only possible due to the characteristics that these software have to make the virtual environment audible. The task is performed by simulating the binaural room impulse response (BRIR) at each receiver position and then convolving it with some anechoic signal. The result, called auralization (Kleiner; Dalenbäck; Svensson, 1993), furnish to the listener the sensation of being immersed in the environment. However, there remains some doubts as to whether the effectiveness and reliability of the hearing aids are sufficient to represent the acoustic reality of the real environment (Brinkmann *et al.*, 2019).

The room acoustics integrated and optimized software (RAIOS) computer code is a room acoustics simulation tool developed in an academic domain in Brazil, capable of generating AVR. The core of this research is to investigate the level of reliability of the auralizations generated by the software in comparison with measured ones, through subjective tests. It is expected that the test results will validate the software, and indicate unsatisfactory aspects of the generated auralizations.

THEORETICAL FRAMEWORK

In 2014, a research called Spatial Audio Quality Inventory (SAQI) proposed a methodology to evaluate spatial audios by correlating them to parameters that qualitatively characterized those sounds (Lindau *et al.*, 2014). Therefore, a common vocabulary (in English) with the main perceptual attributes associated to spatial audio was established. In this way, comparisons between audios originated from simulation and those produced from measurements began to have a standard. More recently, a Room Acoustic Quality Inventory (RAQI) have been published, focusing in performance arts (Weinzierl; Lepa; Ackermann, 2018).

The publishing of the Benchmark for Room Acoustical Simulation (BRAS) provides a database for room acoustics simulation and is a reliable and permanently available to researches and developers of simulation software (Brinkmann *et al.*, 2021). The scenarios of several rooms were carefully acoustically measured and are an excellent reference for corresponding simulations. In this research, the largest and most complex room of BRAS, Scenario 11, was used

for the perceptual comparison between measured and simulated auralizations.

METHODOLOGY

This section presents the simulations to obtain the monaural and binaural room impulse responses, the criteria listed for choosing the SAQI parameters, the sound signals used in the subjective tests, the method of evaluating the perceptual tests, the instrumentation and computational functions used to set up and perform the tests, and how the individuals were trained to perform them.

The Considered Room

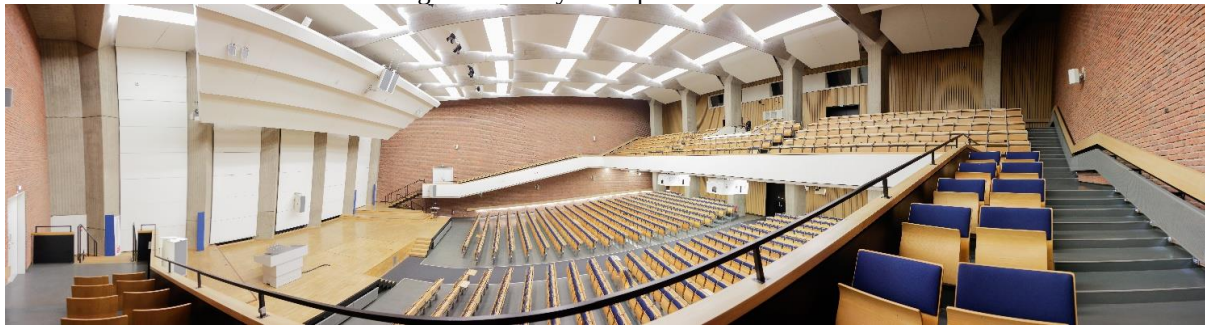
The Auditorium Maximum, Scene 11 of BRAS, is the enclosure used in this research. It has 8,650 m³ and a capacity for 1.192 seats. Figs. 1 and 2 illustrate the interior of the auditorium.

Figure 1. Internal view from the mezzanine, showing the positions of the sound source and the dummy head.



Source: Brinkmann *et al.*, 2021.

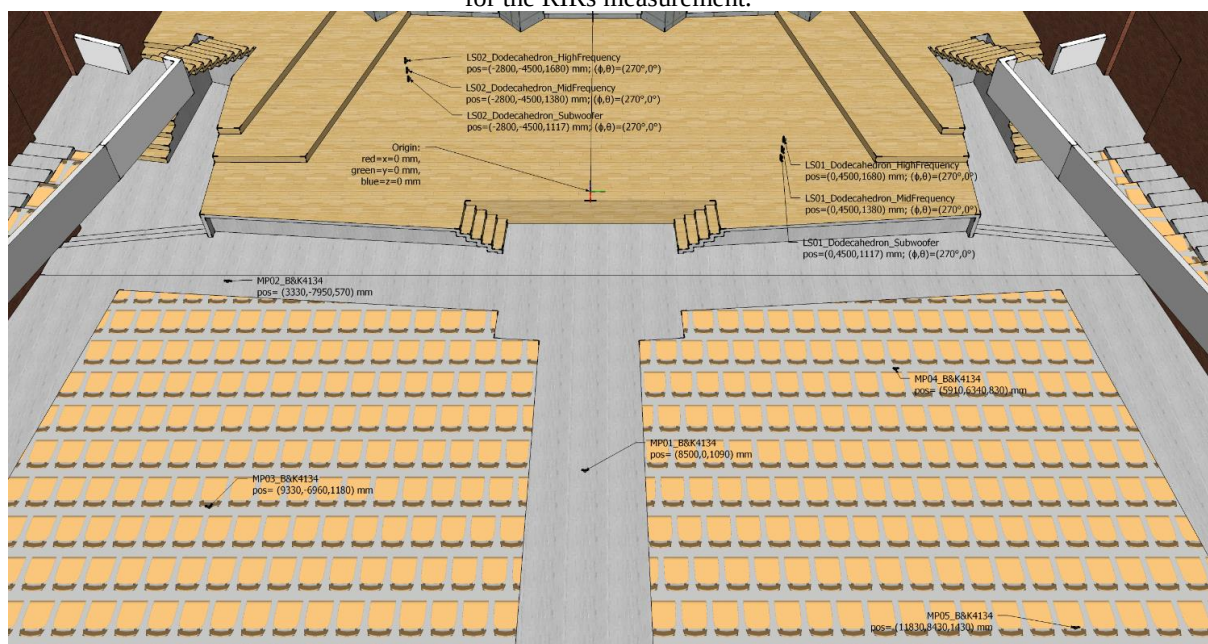
Figure 2. Fisheye side panoramic view.



Source: Brinkmann *et al.*, 2021.

Figure 3 shows in a SketchUp file the positions of the two omnidirectional sound sources and 5 microphones for the measurement and simulation of the 10 room impulse responses (RIRs). Note that the sound source positions and also receivers localizations are distinct for RIRs and BRIRs measurements.

Figure 3. Drawing in SketchUp with the two 3-way source positions (LS01 and LS02) and the 5 receiver positions for the RIRs measurement.



Source: Brinkmann *et al.*, 2021.

The Software RAIOS

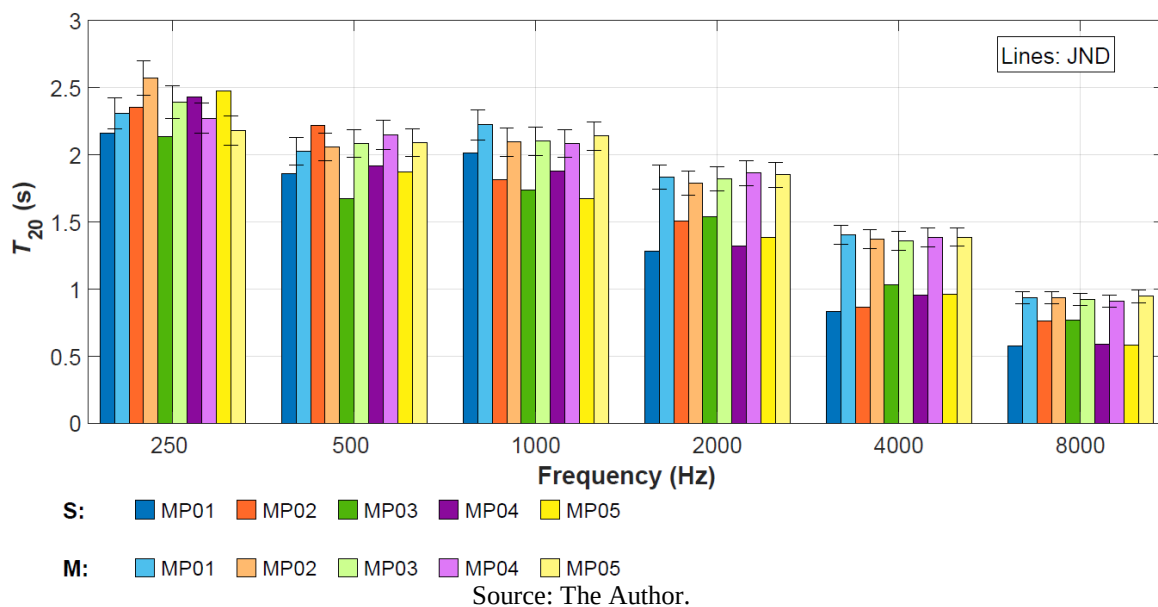
The software RAIOS uses an hybrid algorithm to combine the classical ray-tracing method to compute the specular reflections and the energy-transition method (Alarcão; Bento Coelho; Tenenbaum, 2000) to calculate the diffuse reflections (Tenenbaum *et al.*, 2007a;

Tenenbaum *et al.*, 2007b). In the binaural section, the head-related impulse responses of the dummy head are taken from the Fabian head (Brinkmann *et al.*, 2017), the same view in Figure 1. The calculation method adopted by RAIOS' version 7 supresses the convolutions, classically used in the calculation of BRIRs, by adopting radial basis functions type of artificial neural networks (Haykin, 2009), which results in a technique interely performed in the time domain. This allows a reduction in computational cost in the calculation of BRIRs of around 90% (Tenenbaum *et al.*, 2018; Taminato, 2018; Tenenbaum; Taminato; Melo, 2020).

The Simulations

The first step in the simulations was to compute the RIRs for the 10 source-receiver pairs and to compare them with the measured ones. Figure 4 shows the comparative results of the measured and simulated by software RAIOS 7 reverberation time — estimated by the T_{20} parameter — as a function of the octave band between 250 Hz to 8 kHz, for LS01 and the 5 receivers.

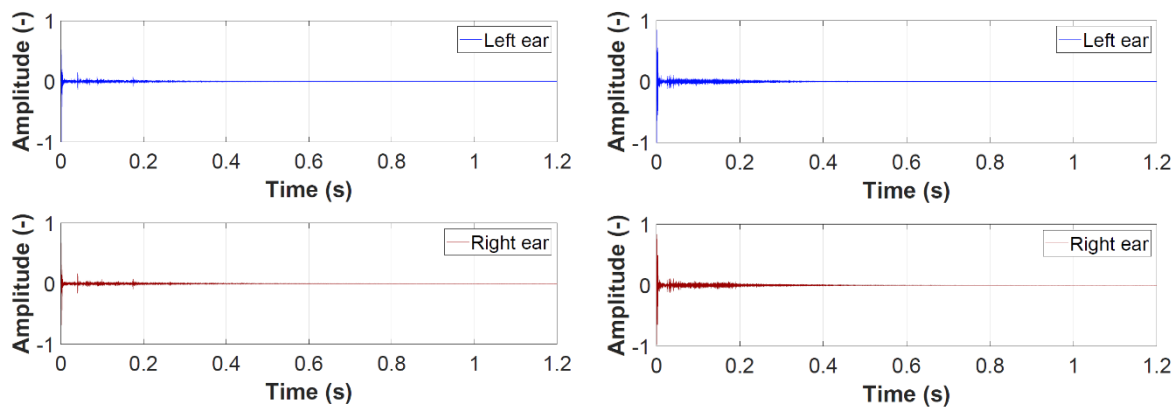
Figure 4. Measured and simulated parameter T_{20} for source position LS01 and the 5 microphone positions, as a function of octave frequency band.



As can be observed from Figure 4, most of the differences in the values of T_{20} are above the just noticeable difference (JND), mainly in the high frequencies. For most receivers, simulated values stay lower than measured values.

The second step in the simulations is to compute the BRIRs for the dummy head location and all five sound source positions. Figure 5 shows the simulated and the measured BRIR for the source-receiver pair shown in Figure 1.

Figure 5. Simulated (left) and measured (right) binaural room impulse responses for the source-receiver position shown in Figure 1.



Source: The Author.

Visually, some difference may be observed between the measured and simulated responses. However, only the subjective tests will adequately assess these differences.

The Anechoic Signals

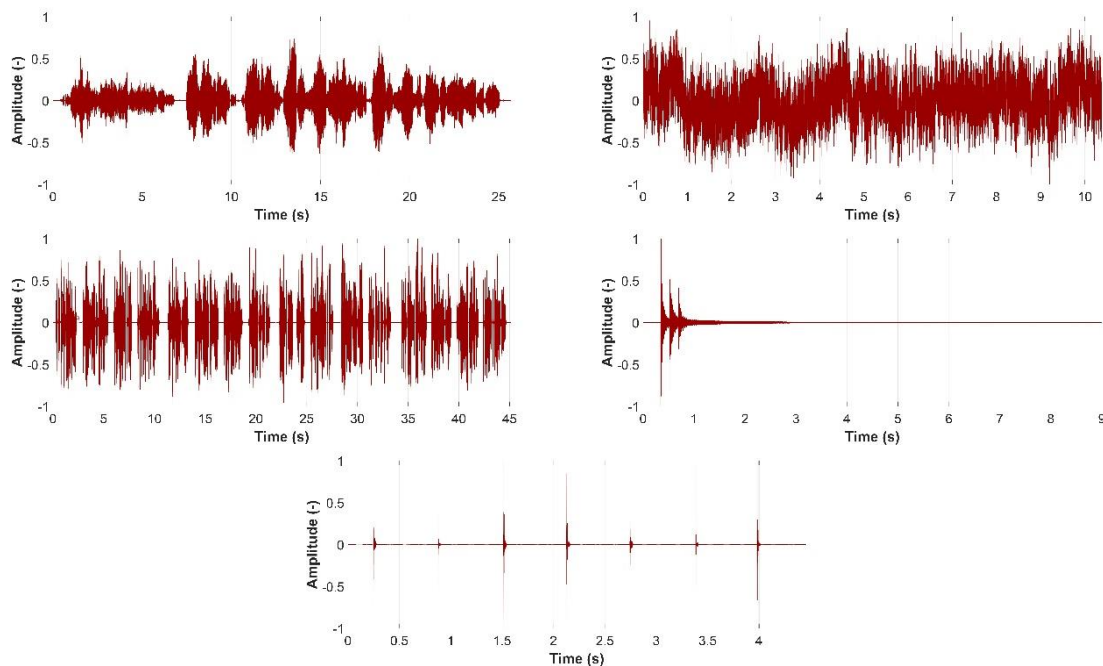
Next, the anechoic signals to be used in the subjective tests were chosen. Five distinct types of signal were selected: 1. a music; 2. a broad spectrum noise; 3. a speech; 4. a percussion instrument; and 5. a transient noise. These were as follows.

- a) The chosen music was an excerpt from the aria Donna Elvira, from W.A. Mozart's opera Don Giovanni. The piece was performed in an anechoic chamber by the orchestra of Aalto University, Finland. For this work, only a 25-second excerpt was selected (Pätynen; Pulkki; Lokki, 2008);
- b) The broad spectrum noise chosen was pink noise, due to its higher low-frequency spectral content. The signal was generated with MATLAB software, with approximately 10 seconds of duration;
- c) The anechoic sound chosen for speech was an excerpt from the poem "Violões que Choram" by Cruz e Sousa. The 45-second recording was made available in the free trial version of the ODEON room acoustics software version 18;

- d) The percussion instrument used was a Tibetan hand bell and the signal was recorded in a small anechoic camera by the authors;
- e) The transient noise chosen is a clapping sequence recorded at the anechoic chamber of Inmetro, the metrological institute of Brazil.

Figure 6 shows the time plot of the five anechoic signals.

Figure 6. Temporal normalized plot of the anechoic signals adopted in the study: music (upper left); noise (upper right); speech (middle left); bell (middle right); and claps (lower center).



Source: The Author.

Subjective Tests

At the beginning, a pre-test was conducted with the aim of listing the SAQI parameters that are most identifiable by the volunteers. A questionnaire with all the 48 terms was presented and they were asked to answer (yes/no) if they identified the SAQI characteristic in any of the signals heard. Five signals of the same types as those used in the subjective test were used, however, the sounds chosen were different from those used in the subjective evaluation. The volunteers listened to the signals in a loop while writing down their answers. By the end, ten SAQI attributes were selected that all volunteers considered 100% identifiable.

The perceptual test was carried out with 26 individuals with good hearing health and belonging to the Acoustic Engineering Program at Federal University of Santa Maria, aged between 18 and 30. They evaluated, using a form, the degree of perception of the 10 selected

descriptive parameters of the SAQI in the spatial audio presented, for the auralizations generated with the five anechoic signals convolved both with the measured and simulated BRIRs.

A preliminar training was provided to teach individual in an expository-dialogued manner to what each of the 10 parameters of the auditory listening point test means. The signals selected for this document include two example signals for each category.

For the test itself, 10 tables were presented for each of the 10 spatial audios. Each table contains four columns that designate different degrees of perception as +, $\pm$, – or **NA** (not applicable). Since the perception of a parameter is dichotomous, the mathematical symbols + and – represent each part of this dichotomy, while $\pm$ represents an intermediate perception; **NA** is for cases in which the parameter does not apply to the spatial audio, or in cases in which the listener was undecided. In order to gather all the results, a larger table was created containing the comparisons of each of the simulated and measured spatial audios with the percentages of the listeners' responses to the degrees of parameters' perception. It is important to note that the signals were heard by the volunteers without any information or differentiation between the measured and simulated auralizations.

RESULT AND DISCUSSION

This section presents the main findings of the research together with some discussion about them.

Pre-tests

The results of the pre-test to list the parameters most identifiable by the volunteers are presented in Table 1. Fifteen parameters out of the 48 verbal decriptors of SAQI were considered as the most perceptible, with scores of 90% or 100%. However, only ten terms obtained 100% of recognition, thus delimiting the test conditions. In orther words, only the ten parameters that achieved 100% of recognition were used in the subjective tests.

Table 1. More identifiable parameters, category to which they belong and degree of adhesion obtained

Parameter	Category	Adhesion (%)
Tone color (bright/dark)	Timbre	100
Sharpness	Timbre	100
Metallic Tone color	Timbre	100
Distance	Geometry	100
Depth	Geometry	100
Localizability	Geometry	100
Level of reverberation	Room	100
Duration of reverberation	Room	100
Loudness	Dynamics	100
Speech intelligibility	General	100
Roughness	Timbre	90
Tonalness	Tonalness	90
Pitch	Tonalness	90
Vertical direction	Geometry	90
Clarity	General	90
Naturalness	General	90

Source: The Author.

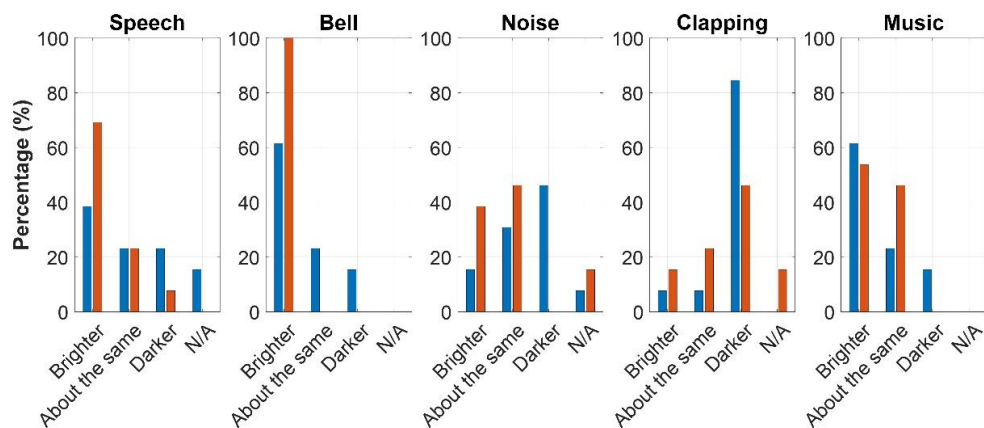
Perceptual Tests

The analysis of the subjective test is separated by perceptual attribute and is presented in this section by using bar graphs in percentage. For each of the auralizations, that is, for each one of the five auralized signals, the graphs from Figure 7 to Figure 16 shows the indications corresponding to the responses +, -, ± and **NA**, furnished by the volunteers. The blue bars indicates measured auralizations, while the red bars refer to simulated auralizations.

Tone Color

All sounds originated by simulated auralizations obtained a brighter tone color indication in relation to the measured pairs, with the exception of the sound of music. In general, according to the volunteers, the measured and simulated sounds of speech, bell and music have a brighter tone than the others, the sound of clapping has a darker tone than the others and, for the pink noise, there was no consensus.

Figure 7. Comparative results of the perceptual attribute tone color for the five kinds of sound signals (blue measured and red simulated).

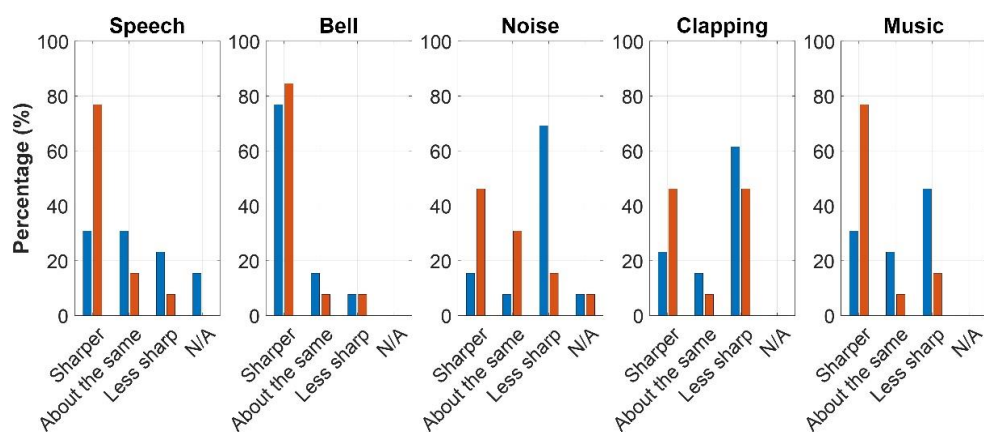


Source: The Author.

Sharpness

All sounds of simulated origin indicated a greater sharpness, and those of measured origin indicated a lesser sharpness, with the exception of the bell sound, which did not present a significant difference between simulated and measured. In general, the measured and simulated speech and bell sounds presented greater perceived shrillness than the others.

Figure 8. Comparative results of the perceptual attribute sharpness for the five kinds of sound signals (blue measured and red simulated).



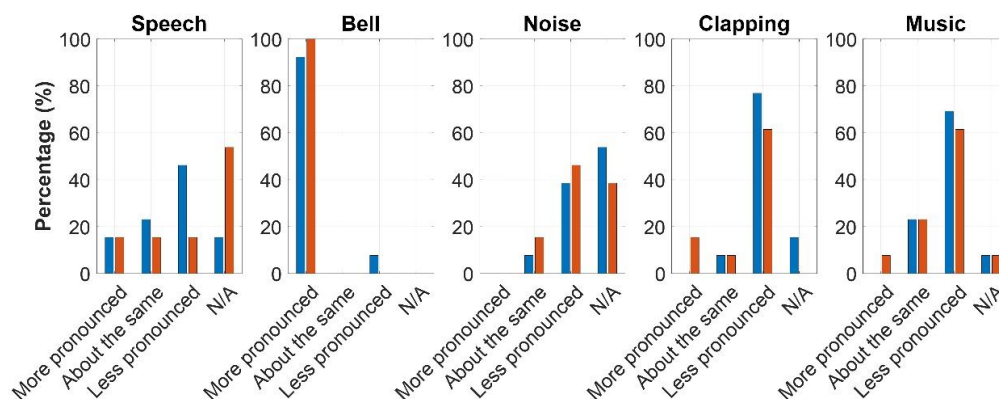
Source: The Author.

Metallic Tone Color

The sounds of simulated origin of bells, clapping and music were those that had the most pronounced metallic tonal color perception in relation to the measured pairs. The speech and pink

noise did not present any difference between the pairs in this regard. However, the perception of a less pronounced metallic tone was the majority for all the measured sounds in relation to the simulated ones, with the exception of pink noise, which did not show any significant difference between the pairs. In general, only the simulated and measured bell signal presented a more pronounced perception, the others were less pronounced.

Figure 9. Comparative results of the perceptual attribute metallic tone color for the five kinds of sound signals (blue measured and red simulated).

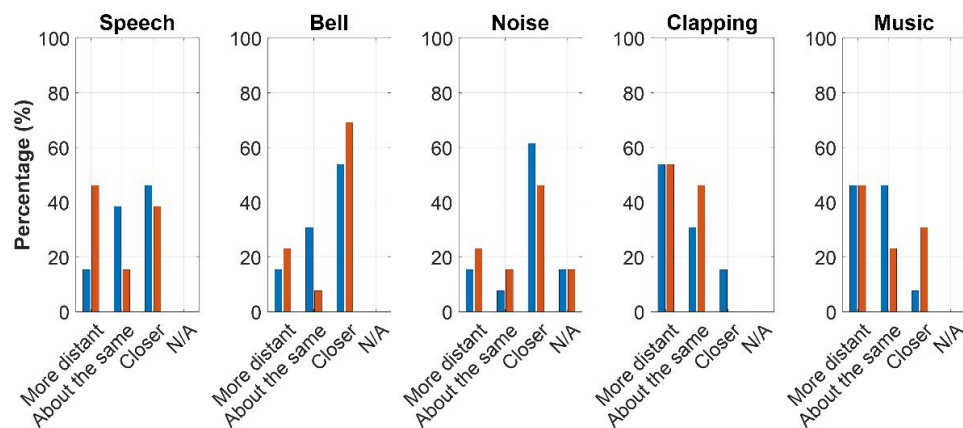


Source: The Author.

Distance

The simulated speech, bell, and pink noise sounds were perceived as being further from the source than their measured counterparts. While the clapping and music sounds did not differ from their peers in this regard. The sounds perceived as being closest to the simulated source were the bell and music, and the sounds perceived as being closest to the measured source were speech, clapping, and pink noise. Overall, the simulated and measured clapping and music signals were perceived as being further away, and the bell and pink noise signals were perceived as being closest. There was no consensus regarding the simulated and measured speech sounds.

Figure 10. Comparative results of the perceptual attribute distance for the five kinds of sound signals (blue measured and red simulated).

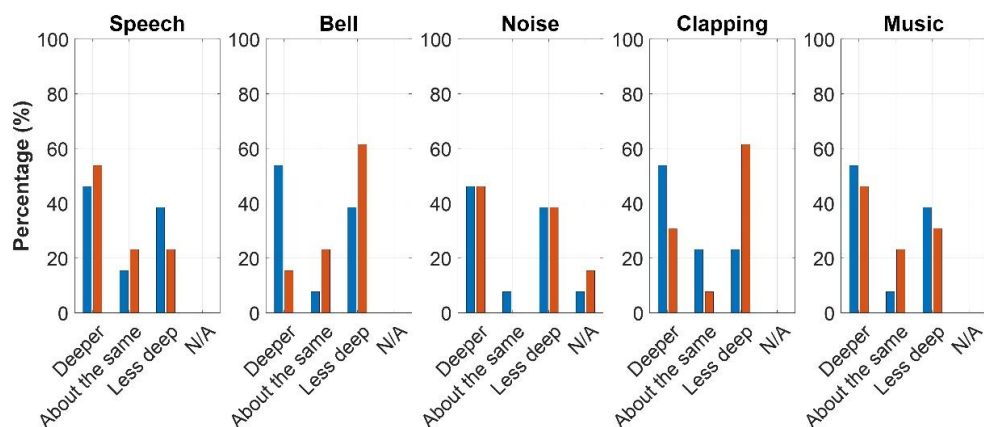


Source: The Author.

Depth

The measured bell, clapping and music signals presented greater depth than their simulated counterparts, while the simulated speech signal presented greater depth than its measured counterpart. The simulated and measured pink noise signals did not present any difference in perception for this aspect or for the lowest depth. The simulated bell and clapping signals presented a less deep perception than their measured counterparts. The measured speech and music signals presented less depth than their simulated counterparts. In general, the measured and simulated speech, pink noise and music signals presented greater depth perceived by the volunteers than the other signals.

Figure 11. Comparative results of the perceptual attribute depth for the five kinds of sound signals (blue measured and red simulated).

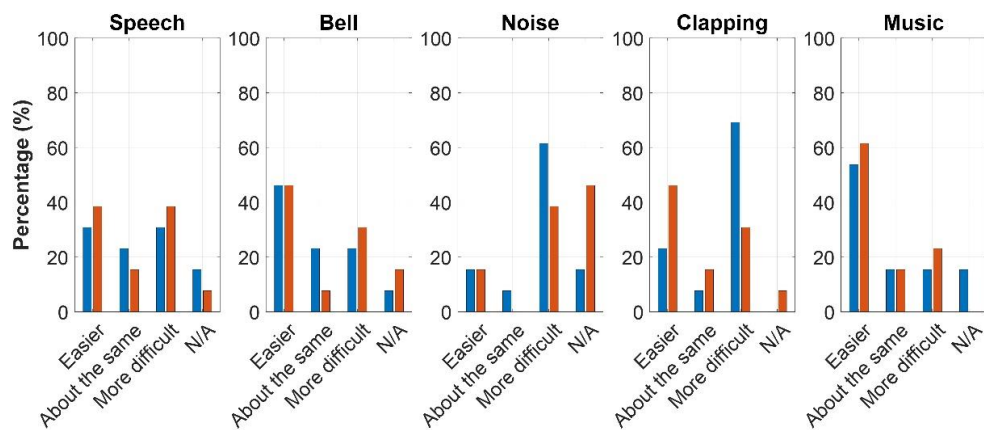


Source: The Author.

Localizability

The simulated speech, clapping and music signals were easier to locate than their measured counterparts. The other signals did not show differences between simulated and measured signals in this regard. However, the measured clapping and pink noise signals were more difficult to locate than the simulated ones. Overall, the simulated and measured bell and music signals were the easiest to locate. Speech sounds were perceived as easier and more difficult in the same proportion. Pink noise and clapping were more discrepant.

Figure 12. Comparative results of the perceptual attribute localizability for the five kinds of sound signals (blue measured and red simulated).

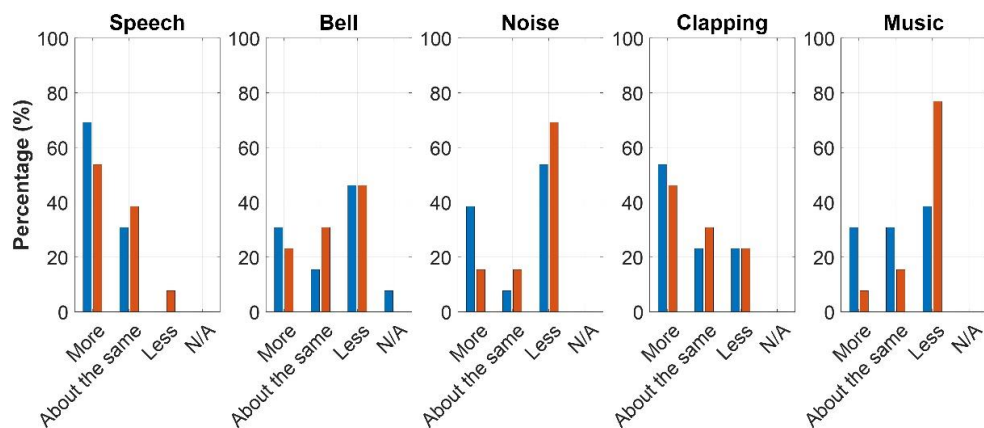


Source: The Author.

Level of Reverberation

All measured signals showed a high perception of reverberation level compared to the simulated signals. The simulated speech, pink noise and music signals showed a lower perception of reverberation level than their measured counterparts. The simulated bell and clapping signals were perceived in the same way as their low-reverberation-measured counterparts. Overall, the measured and simulated speech and clapping signals were perceived with high reverberation levels and the bell, pink noise and music signals with low reverberation levels.

Figure 13. Comparative results of the perceptual attribute level of reverberation for the five kinds of sound signals (blue measured and red simulated).

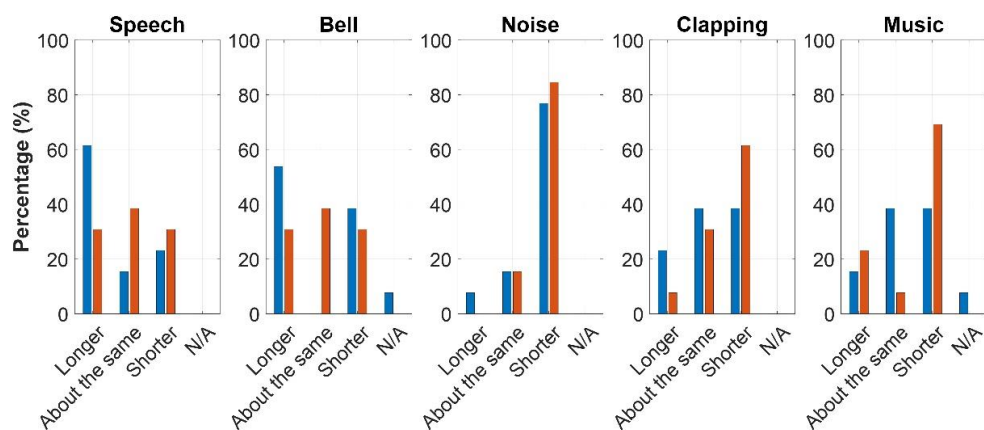


Source: The Author.

Duration of Reverberation

The measured speech, bell and clapping signals were perceived as having a longer reverberation duration than their measured counterparts. The simulated pink noise, clapping and music signals were perceived by volunteers as having a shorter reverberation duration than their measured counterparts. Overall, the measured and simulated pink noise sound was perceived by volunteers as having a shorter duration; for the other sounds, there was no mutual consensus between the measured and simulated sounds regarding the other quality levels.

Figure 14. Comparative results of the perceptual attribute duration of reverberation for the five kinds of sound signals (blue measured and red simulated).

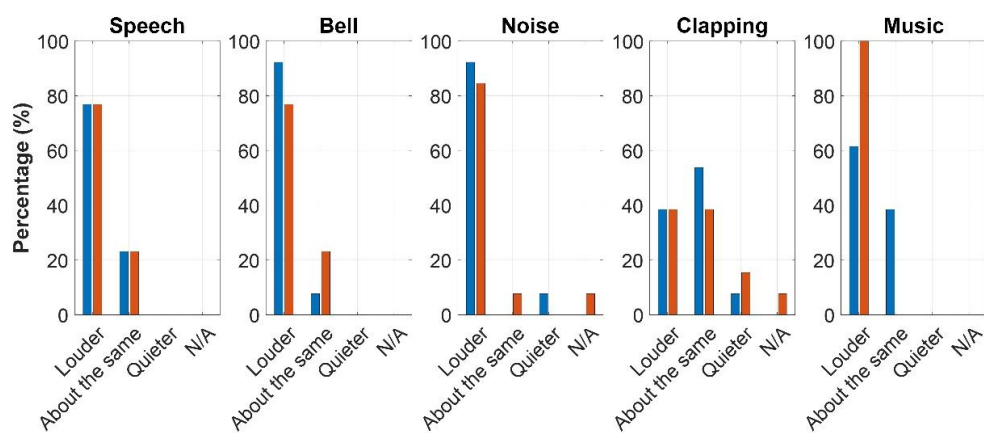


Source: The Author.

Loudness

The simulated music sound was perceived with higher audibility than its measured pair, while the measured bell and pink noise sounds were perceived with higher audibility than their simulated pair. Overall, all simulated and measured sounds indicated higher audibility, with the exception of the clapping sound, in which there was no consensus. The speech sound also showed no difference between the measured and simulated sounds.

Figure 15. Comparative results of the perceptual attribute loudness for the five kinds of sound signals (blue measured and red simulated).

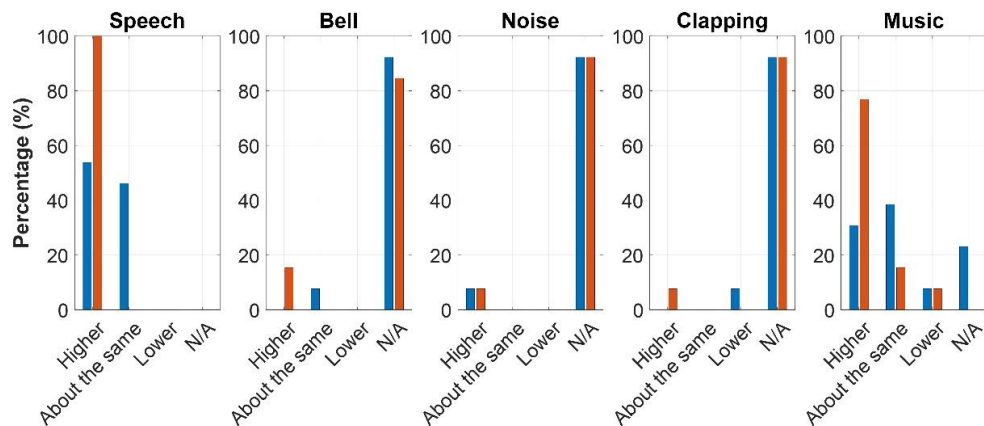


Source: The Author.

Speech Intelligibility

Only speech and music sounds were considered for the analysis of this parameter. The simulated signals presented higher percentages of perception of superior intelligibility in relation to the measured ones. For music, however, there was no consensus.

Figure 16. Comparative results of the perceptual attribute speech intelligibility for the five kinds of sound signals (blue measured and red simulated).



Source: The Author.

Difference Ranking for the Music Signal

The music signal was considered as the most complex for this analysis, since its spectrum is composed of different timbres, such as that of a soprano's voice and that of a cello, by the reverberation of the room, by the variation in the pitch of the notes and by the controlled dynamics of the musicians' performance. The level of similarity between the simulated auralization and its measured pair was ranked for the ten parameters studied in the SAQI and for the + quality level. Table 2 presents the module of the differences between the test results for simulated auralizations and their measured pairs in ascending order. The smaller the difference, the greater the perceived similarity between the simulated and measured sound by the volunteers.

Table 2. Ranking of the considered ten perceptual terms considering the differences between simulated and measured auralizations for the music signal.

Parameter	Difference
Distance	0
Tone color	7,7
Metallic Tone color	7,7
Localizability	7,7
Level of reverberation	7,7
Duration of reverberation	7,7
Depth	7,7
Loudness	23,1
Speech intelligibility	46,1
Sharpness	46,1

Source: The Author.

CONCLUSION

According to the results obtained in the subjective tests, differences and similarities were found between auralizations originating from simulated BRIRs and those originating from measured BRIRs. When there was perceptual similarity between simulated and measured auralizations, the parameter is said to have converged; when there were perceptual differences in which simulated and measured sounds behaved antagonistically for all or most of the signals, the parameter is said to have diverged. If the parameter diverged and there was no antagonistic behavior pattern between the auralizations, the parameter is said to be inconclusive.

In the Timbre category, the bright-dark tone color parameter diverged, indicating a greater perception of high-frequency content (brighter tonal color) in auralizations with simulated BRIRs. In contrast, the same parameter indicated a greater perception of low-frequency content in auralizations with measured BRIRs (darker tonal color). The perceptions of sharpness also diverged, and those identified for the simulated signals were mostly more shrill, while for the measured signals, less shrill. Finally, the perception of metallic tonal color was convergent for both types of auralizations.

Among the parameters in the Geometry category, two presented convergent results between simulated and measured sounds, such as the perception of distance and location — with only divergence between the results for a few sounds, such as clapping for location and speech for both. In depth perception, the results diverged for most simulated and measured sounds, but

inconclusively.

For the parameters of the Room category, the reverberation level and reverberation duration obtained convergent perceptual results for most auralizations, indicating a similarity between them. However, only in two auditory signals originated from simulation: the bell and speech signals, the perception of reverberation duration diverged.

The audibility parameter, of the Dynamic category, had a convergent perception for both types of auralizations and for all signals. Furthermore, the speech intelligibility parameter, of the General category, was also convergent for both types of auralizations, analyzed only for the speech and music signals. Table 3 summarizes the convergence/divergence of the auralizations with reference to the spatial audio parameters considered in this research.

Table 3. General judgment of the 10 parameters analyzed regarding convergence (C), divergence (D) or inconclusiveness (I) in the comparison between the measured and simulated auralizations.

Parameter	Category	Judgment
Tone color	Timbre	D
Sharpness	Timbre	D
Metallic Tone color	Timbre	C
Distance	Geometry	C
Depth	Geometry	I
Localizability	Geometry	C
Level of reverberation	Room	C
Duration of reverberation	Room	C
Loudness	Dinamycs	C
Speech intelligibility	General	C

Source: The Author.

In the distance parameter there was one divergent signal among the five and in the reverberation duration and localization parameters there were two divergent signals.

ACKNOWLEDGEMENTS

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