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A BRIEF OVERVIEW OF SOUND REPRODUCTION SYSTEMS FOR LISTENING TESTS USED IN THE SUBJECTIVE EVALUATION OF SOUND INSULATION

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Abstract: *This article does not present an in-depth overview but is meant to serve as an introduction to the newcomers to this field of acoustics. A brief explanation is given for different sound reproduction formats (Ambisonics and binaural), together with some of the standards, and listening test tools used in the design of listening tests. Primarily the listening tests in the field of subjective evaluation of sound insulation and acoustic comfort have been discussed.*

Keywords: *acoustic comfort, listening tests, perceptual audio evaluation, Ambisonics, binaural, sound reproduction systems*

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1. INTRODUCTION

Acoustics has been a part of human civilization for thousands of years, which can be seen in amphitheaters of ancient Greek and Rome, but also in even older structures like the Stonehenge [1]. These structures have mainly been used as ritual or entertainment establishments and throughout history mostly the higher class was the one with enough time and resources that its everyday existential and security struggles were negligible enough to even consider thinking about acoustics. Since most of their dwellings were made of stone or wood, it can be assumed that they did not have many problems with sound insulation at the time. It was not until the rapid technological expansion and migration of people to higher density areas that the first serious steps into modern building acoustics took place.

With the industrial revolution and new technology, the standard of living became higher, and at the half of the 20th century the middle class could afford a better standard of living than the higher class one century ago; but with the movement of the working force from the villages to the big industrial cities in the search for better life and job, people started occupying multi-family housing. The new living environment brought up new challenges, of which the common one was the question of sufficient sound insulation between dwellings. The first ISO norms that addressed this question were for measuring and rating of sound insulation in 1968 and in 1978 respectively, with their latest installments being ISO 10140 and ISO 717 standards.

Most multi-family buildings are, even today, built using concrete or masonry wall constructions and they are the most explored materials in building acoustics. With the popularization of modern lightweight constructions, that began during the late 20th century, new problems were reported, especially in the frequency range below 100Hz, which was not part of the spectrum that was used for the calculation of standard single-number quantities at the time. [2]

The first mention of acoustic comfort in relation to building acoustics was used by Cummins (1978) [3]. Rindel and Rasmussen (1995) [4] characterize acoustic comfort as (1) Absence of unwanted sound (2) Presence of wanted sound of the desired level and quality (3) Opportunities for acoustic activities without annoying or disturbing other people without being heard by unauthorized persons.

The study conducted between 1992 and 1994 by Grimwood (1997)[5] showed that people living in buildings with poor sound insulation reported not only annoyance of the noise coming from neighbors but also a level of concern about some of their behavior being the source of noise for other members of the dwelling e.g. This indicates that poor sound insulation can be a potential source of conflict, but also a restricting factor on residents' behavior. [6].

Some studies that investigated acoustic comfort in building acoustics used ISO/TS 15666 assessment of noise annoyance using social and socio-acoustic surveys. This type of survey is restricted to obtaining the information about the annoyance "at home", so it can be viewed as an in-situ measurement of the perceptual evaluation of sound insulation. The main benefit of this type of survey is that the results always convey real-life situations, it is not an artificially constructed situation. This can help determine what type of problem actually requires a solution and what is its level of priority.

On the other hand, their downside is that they are restricted to a single listening environment without an option to make comparisons with any other wall or ceiling material or configuration. Also, since the survey is made by asking participants about their everyday experiences, the results are prone to a lot of unwanted noise in the results data (e.g. their memory, relationship with the neighbors and the neighborhood, physical and mental state of the participant at the time of the survey,...). In recent years, the subjective evaluation of sound insulation has been investigated using listening tests in controlled laboratory conditions ([7-10]). A controlled environment provides opportunities to test some of the aspects of sound insulation more precisely with the possibility to test different configurations without moving a person to another room. Even if it is possible to organize the movement of the participant to a new dwelling, that would still be a problem because changing the visual stimuli of the listener could also influence our audio perception which would again introduce unwanted uncertainties to the test.

The negative aspect of listening tests is that the aesthetic of the laboratory environment usually does not resemble living room conditions. That makes it impossible to investigate the level of annoyance of noises because they are situation dependent i.e. the same sound stimuli could provide the biggest pleasure while in other situations it would be painful and annoying to listen to (e.g. a loud rock or pop song on a live concert or a party vs. relaxing or high focus situations). Instead, different types of comparison of audio samples are used for as well as a semantic differential test. [2]

Other important considerations for listening tests in building acoustics are the sufficiently low background noise, proper acquisition and preparation of the listening samples, and the choice of the reproduction system. Background noise in the listening space should not exceed 10dB below the lowest level of the quietest stimuli in each third-octave band [2]. Samples should be acquired in such a way that it is possible to reproduce it faithfully, but also that it represents the worst-case scenario in the examined situation (e.g. the heel walking in case of impact noise listening tests [11]).

Finally, the choice of the sound reproduction system in these types of experiments have not been studied extensively, but there are still some intuitive general requirements that should be considered. Two main choices are either headphones or some configuration of loudspeakers. The type of reproduction system should cover the entire frequency range present in the stimuli signal, so there is no loss of information across the spectrum. Calibration of the system should also be done to achieve a flat frequency response. In case without the proper calibration it could happen that e.g. while comparing perceived loudness of walking noise of different floor configurations one of the samples has a resonance at 100Hz and another one at 80Hz, with the system having a dip in the spectrum at 100Hz, the listener would probably asses that the 80Hz sample is louder, even if that is objectively not the case, due to the unbalanced reproduction system.

Some studies have shown that there is not a significant difference between the usage of headphones and 3D audio reproduction systems while conducting listening tests [12-13]. Nonetheless, the research questions investigated in those studies have been broadly stated and have not regarded the listening tests conducted in the research of acoustic comfort, which includes the subjective evaluation of sound insulation.

This article presents a partial overview of the benefits and downsides of Ambisonics and binaural formats for performing listening tests. Although Ambisonics can be decoded even into a binaural format, the comparison considered is mostly made between the basic reproduction of the two formats: multi-channel loudspeaker system reproduction for Ambisonics and headphone reproduction for binaural. The idea is to focus on the part of the listening test methodology that looks at the advantages and disadvantages of using a 3D audio reproduction system compared to much simpler and less expensive headphones setups for listening tests and what situations would be appropriate to use one or the other.

This is by no means meant as an extensive tutorial on this topic, but just an overview of fundamental considerations about the sound reproduction system for this type of listening tests, and also some of the available listening test tools and standards used today in listening tests are mentioned as well.

2. WHY TO EVEN DO LISTENING TEST?

Sound is a very multidimensional phenomenon. Some of its properties are purely physical and can be measured in the form of speed, air pressure amplitude, velocity, or acceleration, the same as concepts like loudness, intensity, energy, pitch, timbre [14]. Nonetheless, human perception of sound and the influence of sound on people is a much more complex problem [15]. Unfortunately, it is still not possible to put a metering device directly on listeners and get a specific number out of it, although the popularity of research of measuring EEG [16], EKG [17], and other physiological signals responses on audio stimuli have been on the rise in the last a couple of decades.

The alternative way of assessing how listeners perceive audio is to ask them directly to quantify their experience. This is the most common form of perceptual evaluation that often takes the form of a formal listening test [15]. Although testing of audio quality and other properties of sound reproduction systems have been existing in some form of listening tests ever since the first "Mr. Watson, come here. I want to see you." that was said at Graham Bell's Lab, many improvements in the listening test methodology have been made over time. Since all listening tests have to take into consideration the uncertainty of the measurement linked with the human factor, it is a field of science that is still being explored extensively.

3. AMBISONICS

3.1. What is Ambisonics?

"Ambisonics is a method of codifying a sound field considering its directional properties. In traditional multi-channel audio (e.g., stereo, 5.1 and 7.1 surround) each channel has the signal corresponding to a given loudspeaker. Instead, in Ambisonics each channel has information about certain physical properties of the acoustic field, such as the pressure or the acoustic velocity." [18]

Ambisonics is a full-sphere surround sound format. In listening test application Ambisonics is usually used with a multi-channel reproduction system that consists of speakers placed around the listening sweet spot in the listening plane, but also on the floor and the ceiling. An example of a listening room enhanced with an Ambisonics system can be found in [19].

The fundamental theory of Ambisonics can be divided into a couple of basic principles:

3.1.1. At zeroth-order: Ambisonics has information about the pressure field at the origin (recording of an omnidirectional microphone at the origin). The channel for the pressure field is conventionally called W.

3.1.2. At first-order: Ambisonics adds information about the acoustic velocity at the origin (recording of three figure-of--eight microphones at the origin, along each one of the axis). These channels are called X, Y, Z. Following the Euler equation, the velocity vector is proportional (up to some equalization) to the gradient of the pressure field along each one of the axis.

3.1.3. At second and higher-order: Ambisonics adds information about higher-order derivatives of the pressure field. [18] The ambisonics recording is usually recorded with a specialized 4 channel microphone which provides an A format recording. That kind of microphone usually has four capsules placed in a tetrahedron configuration, e.g. RODE NT-SF1 microphone. Ambisonics A format corresponds to the direct recordings of each of the four capsules of the microphone. Ambisonics recordings are never kept in the A format but are rather transformed into a B format. B format also has four channels, but it corresponds to the omnidirectional information (W), and three directional channels where each channel holds the information about one of the axes (X, Y, Z). Although this gives the complete information about the spatial sound, before playback, B format must be recorded into C, D or G formats that carry signal information for each of the loudspeaker channels of the reproduction system.

3.2 In which fields and situations is it used?

Although Ambisonics had its beginnings with Michael Gerzon in the 1970s [20] with the basic principles dating all the way back to the 1930s [21], it was not met with commercial success at that time. During the 1990s the theory of higher-order Ambisonics (HOA) was founded, which brought new light on to Ambisonics format, and it remains a topic of research in the academic community today [22]. Lately, Ambisonics found new applications with the increasing popularity of virtual reality [23-24] but also as a sound reproduction system for listening tests [8]. It was even used as a format of audio distribution for different venues and broadcasts in real-time [25]

The growing internet community opened a new possibility to experience virtual reality (VR) enhanced with surround sound. Platforms such as Youtube [26], Google [27], Facebook [28] started creating a framework for VR which would include and allow integration of spatial audio.

Furthermore, audio production companies started the development of tools for easier manipulation and transformation of spatial audio signals that can be easily used with existing digital audio workstations (DAWs) with a similar workflow as a traditional production of audio, which is supporting a smoother transition to novice technologies [29-36].

3.3 Pros and cons of Ambisonics

3.3.1. Pros: Bigger potential number of participants at the same time. Real feel of the situation, i.e. people do not usually sit at home in an empty room and listen to sounds on headphones. Fully immersive surround sound which would mean that the sound is heard by the listener from every direction, 360 degrees and up and down directions. Perceived spatial localization properties can be improved by the rotation of the head [37]. A relatively small number of audio channels is needed to describe complete surround sound spatial audio. [22]. Ambisonic formats are independent of the reproduction system; i.e. an Ambisonics signal can be decoded to any loudspeaker configuration or for binaural or transaural rendering [38-41].

3.3.2. Cons: Complexity of equipment for reproduction system, complexity of calibration process, larger file sizes, different conversions, specialized room, cost.

4. BINAURAL

Localization in binaural audio is achieved by perceiving differences in the timing and volume of sound waves hitting two human ears. Considering hardware requirements, binaural listening tests are fairly simple and just require headphones.

The beginnings of the binaural reproduction format happened in 1933 when one of the divisions of Bell laboratories demonstrated a dummy human head with microphones in the ears. The signals from these being played directly back into the hearer's ears using headphones. Around the same time, a Connecticut radio station broadcasted several shows in binaural stereo, using two separate radio frequencies - the listener had to use two separate radios to feed two earphones. Although the idea of binaural recording is attractive, it turns out to have very variable effectiveness for different people, and to be unsuitable for playback through loudspeakers. For these reasons, it has remained rather a niche approach to recording for many years [42].

Nowadays research is still done considering binaural formats, e.g. in the field of Television and film. Lopez et. al. [43] are developing ways of enhancing accessibility for TV and film for the visually impaired.

4.1. *HRTFs vs Mono or Stereo headphone signals, transaural*

There is an important difference that must be made between simple stereo or mono headphone signal, and binaural signals. Stereo and mono headphone signals are made by just simple reproduction of audio signals over the headphone speakers, the same way as it would be reproduced over regular speakers. In the case of binaural reproduction, the signals either need to be modified before reproduction or they need to be recorded with a head and torso simulator i.e. dummy head.

Modifications of the regular audio signal for binaural reproduction are best made by convoluting them with an appropriate head-related transfer function (HRTF). Head-related transfer functions are impulse responses recorded with a dummy head that have microphones mounted inside the ear canal and with the source signal coming from different directions. The set of HRTFs can be made by rotating the dummy head with 1 degree or similar steps in the horizontal plane, but also with a bit more complex rotation in the vertical direction.

Transaural rendering can also be made by using basic binaural configuration but enhancing it with crosstalk cancellation so it can be played back over a pair of speakers. This technology is used in aixCAVE at RWTH Aachen University [44].

4.2. *Head-tracking*

"Head-tracking is a software application that monitors a user's head position and orientation. It is often used alongside face and eye tracking to help and improve human-computer interaction (HCI). Head tracking is often used to simulate the experience of freely looking around in virtual (VR) or augmented reality (AR), allowing the user to experience an immersive and natural way to look around in virtual environments. There are a couple of methods used for head tracking. Screen quality and head-tracking responsiveness are some of the most significant user experience differentiators between high-end headsets, like Oculus Rift, and low-end headsets and smartphone holding designs like Google Cardboard. Devices that use smartphones often rely on phone accelerometers and gyroscopes. High-end headsets have more accurate tracking with precise sensors, along with other systems including infrared LEDs, cameras, and magnetometers. Because head tracking in AR or VR can simulate real-life experiences, it can fool the brain even better than standard viewing for more engaging and immersive user experience." [45]

With head tracking information it is possible to choose an appropriate HRTF that would not rotate an entire sound field but would just allow the listener to move its head during a listening test, which would give a more realistic and immersive feeling to the listening experience.

4.3 Pros and cons of binaural

Since every experiment and application has its specific set of requirements, it must be mentioned that some of pros and/or cons are situation-dependent, this list gives very generalized information.

4.3.1. Pros: In its basic form, a binaural listening test is not as budget consuming as other audio reproduction options. Also, the availability of the system is one of its benefits because headphones are basically part of every household. Listening test rooms that use headphones are usually much less expensive than specialized rooms with specialized multi-channel systems. In the case where there is no specific need for an extremely controlled setup, the experimenters are able to distribute the listening test online to subjects all over the globe, and that way more participants can be reached, and the data set can be much more representing of a general population.

4.3.2. Cons: Downsides of binaural would definitely include a limitation of a natural feeling concerning localization because it is either needed for the head of the participant to remain fixed or to use head tracking with a set of HRTF, which raises the complexity of the system. In the case where there is a movement of the head, a head-tracking enhancement of the system should be engaged.

Headphone positioning variability presents a big problem considering the repeatability of experiments conducted with headphones and binaural [46].

5. STANDARDS

In the field of audio, a number of standards or recommendations cover a wide range of topics, from measurement devices through to perceptual evaluation methods for telecommunications or audio systems. They try to provide information on the best-agreed practice for performing listening tests. Standards do not always suggest the most advanced method, just the best-agreed method. Standards are always application-oriented and should not be used interchangeably. Although it is always a possibility to take a core idea of a standard and modify it to a specific need, at that point, it cannot be called a standardized measurement anymore. [15], [47]

The standardization of listening tests has not gotten yet to the point where specific attributes of the test are stated. In the case of a listening test where more advanced and complex methods need to be used, there are many other studies that could be referenced for their methodology (e.g. [48]). Key organizations are ITU-R and ITU-T.

5.1 ITU-T telecommunication applications

Focused on telecommunication applications, i.e. speech codecs, echo cancellers, etc. Speech oriented, Mean Opinion Score (MOS) based, a mostly narrowband (300 Hz – 3400 Hz), or wideband (100 Hz – 7000 Hz), the usual number of naive assessors is from 12 up to 36. Covers several methods such as Absolute category rating (ACR), Comparison category rating (CCR), Degradation category rating (DCR). Key standard ITU-T P.800. [15]

5.2 ITU-R Radio communication section

Audio applications, e.g. audio codecs, basic audio quality (BAQ) based, full band audio applications (20 Hz – 20000 Hz), a usual number of expert assessors is 20. Key standards are ITU-R BS.1116-1 and BS.1534-1. [15]

5.3 Current key standards and recommendations for performing listening tests

5.3.1 ITU-T Recommendation P.800: [49]

Absolute category rating (ACR): single stimulus method, dependent variable (5–point categorical scale: listening quality, listening effort, loudness preference), Independent variables (system/codec, speech sample, talker gender, sentence, listening level), naive subjects (24-36), ANOVA based analysis.

Comparison category rating (CCR): paired comparison, hidden reference, dependent variable (7–point categorical scale), independent variables (system/codec, speech sample, talker), naive subjects (24–36), ANOVA based analysis.

Degradation category rating (DCR): fixed reference paired comparison, dependent variable (5–point degradation categorical scale), independent variables (system/codec, speech sample, talker, background), naive subjects (32), ANOVA based analysis.

5.3.2 ITU-R Recommendation BS.1116-1 ABC/HR: [50]

Evaluation of small impairment (only), double-blind triple stimulus hidden reference, dependent variable (5–point continuous rating scale: basic audio quality, stereophonic image quality, front image quality, impression of surround quality), independent variables (system/codec, programme, subject), expert assessors (20 with defined selection process), ANOVA based analysis. Listening room definition and loudspeaker setup definition.

5.3.3 ITU-R Recommendation BS.1534-1 MUSHRA: [51]

Double-blind multi-stimulus with hidden reference and hidden anchors, dependent variable (0–100 continuous quality scale with 5 equal intervals, basic audio quality, stereophonic image quality, from image quality, impression of surround quality), independent variables (system/codec, programme, subject), partially screen subjects (more than 20).

6. LISTENING TEST TOOLS

Several tools for the design of listening tests have been developed over the years. "When performing listening tests, audio stimuli are to be presented to subjects and their responses are to be collected. While these steps can be performed manually, this is a highly complex, time-consuming, and very error-prone approach. Nowadays, computer-based systems are available to automate stimulus presentation and/or data collection, avoiding most of the limitations associated with a manual procedure. Such software tools are highly desirable in listening test work to lighten the burden on the experimenter and also to provide better control over the experiment. This latter aspect leads to a reduction in experimental error, as well as providing robustness. Additionally, using a computer-based system allows for similar experiments to be perfectly duplicated or repeated at different locations or times." [15]

Knowledge and use of these tools can save precious development time and money during the experimental design. Although some of them have templates for a lot of listening tests, some of the tools can be modified to a specific need.

The most popular and advanced listening test tools are:
- HULTI-GEN [53]: Max/MSP based, very versatile tool
- WAET [54]: JavaScript/browser-based, very versatile tool
- WhisPER [55]: Matlab-based
- APE [56]: Matlab-based
- Scale [57]: Matlab-based
- MUSHRAM [58]: Matlab-based
- BeaqlesJS [59]: JavaScript-based
- STEP [60]: Windows-based, ITU-R BS.1116-1, ITU-R BS.1534-1, ITU-T P.800 ACR
- webMUSHRA [61]: web-based ITU-R BS.1534-1
- GuineaPig [62]

A side by side comparison of some of these listening test tools can be found in table 1a and 1b.

Toolbox	APE	BeaqlesJS	HULTI-GEN	MUSHRAM
Language	MATLAB	JS	MAX	MATLAB
Remote		(+)		+
MUSHRA (ITU-R BS. 1534)		+	+	+
APE	+			
Rank Scale			+	
Likert Scale			+	
ABC/HR (ITU-R BS. 1116)			+	
-50 to 50 Bipolar with Reference			+	
ACR Scale (ITU-T P.800)			+	
DCR Scale (ITU-T P.800)			+	
CCRating Scale (ITU-T P.800)			+	
9 Point Hedonic Category Rating Scale			+	
ITU-R 5 Continuous Impairment Scale			+	
Pairwise / AB Test			+	
Multi-Attribute Ratings			+	
ABX Test		+	+	

Tab. 1a: Comparison of the listening test tools [52]

Toolbox	Scale	WhisPER	WAET	STEP	GuineaPig
Language	MATLAB	MATLAB	JS		Linux
Remote			+		
MUSHRA (ITU-R BS. 1534)			+	+	
APE			+		
Rank Scale			+		+
Likert Scale			+		
ABC/HR (ITU-R BS. 1116)			+	+	+
-50 to 50 Bipolar with Reference			+		
ACR Scale (ITU-T P.800)			+		+
DCR Scale (ITU-T P.800)			+		+
CCRating Scale (ITU-T P.800)			+		+
9 Point Hedonic Category Rating Scale			+		
ITU-R 5 Continuous Impairment Scale			+		
Pairwise / AB Test			+		+
Multi-Attribute Ratings			+		
ABX Test			+	+	+
Adaptive Psychophysical methods		+			
Repetory Grid Technique		+			
Semantic Differential	+	+	+		
n-Alternative Forced Choice	+				

Tab. 1b: Comparison of the listening test tools [52]

7. CONCLUSION

The subjective evaluation of sound insulation is a young branch of building acoustics, but a very important one. With more people living in multi-family dwellings and with the growing number of materials and configurations of walls and floors being investigated today it is necessary to also have reliable measurement methodology that would help study the perception of its final user, which are in this case the people living inside of those walls. The universally agreed methods of measurement and threshold levels are still being discussed by the acousticians working in this field and still need to be agreed upon[63].

As can be seen, both Ambisonics and binaural approach in listening test design has some benefits, but also some downsides. Future work will focus on further investigating their differences with the goal of finding more specific situations and examples in which it would be beneficial to use one instead of the other. Furthermore, the possibility of expansion of binaural headphone reproduction with a low-frequency subwoofer could give us the best of both worlds, having simplicity of the setup with also the low-frequency vibrations being heard throughout the listener's body.

The position of the low-frequency subwoofer in the listening room is one of the still open questions that would require further research [15].

Further insight into general preparation, setup, and analysis of listening tests can be found in [15], and a bigger focus on listening tests of sound insulation can be found in chapters 6, 7 and 8 of [2].

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REFERENCES

[1] Cox, T.J., Fazenda, B.M., Greaney, S.E.: "Using scale modelling to assess the prehistoric acoustics of stonehenge," Journal of Archaeological Science, vol. 122, p. 105218, 2020

[2] COST Action TU0901, Building acoustics throughout Europe Volume 1: Towards a common framework in building acoustics throughout Europe. DiScript Preimpresion, S. L., 2014

[3] Cummins, D.E.: "Classes of acoustical comfort in houses," Proceedings of Inter-noise 78, pp. 631–635, 05 1978

[4] Rindel, J.H., Bright, R.: "Buildings for the future: The concept of acoustical comfort and how to achive satisfatory acoustical conditions with new buildings," COMETT-SAVIOR Course, 1995

[5] Grimwood, C.: "Complaints about poor sound insulation between dwellings in england and wales," Applied Acoustics, vol. 52, no. 3, pp. 211 – 223, Performance, Analysis and Predictions in Building Acoustics, 1997

[6] Rindel, J.: Sound Insulation in Buildings. CRC Press, 11 2017

[7] Chmelik, V., Rychtarikova, M., Muellner, H., Jambrosˇic´, K., Zelem, L., Benklewski, J., Glorieux, C.: "Methodology for development of airborne sound insulation descriptor valid for light-weight and masonry walls," Applied Acoustics, vol. 160, p. 107144, 03 2020

[8] Chmelik, V., Benklewski, J., Rychtarikova, M., Kisic, D., Jambrosic, K., Horvat, M., Muller, H.: "The preliminary study on subjective rating of different floors characterised by In,w+ci,50-2500," in PROCEEDINGS of the 23rd International Congress on Acoustics, (Aachen, Germany), 2019

[9] Spah, M., Hagberg, K., Bartlome´, O., Weber, L., Leistner, P., Liebl, A.: "Subjective and objective evaluation of impact noise sources in wooden buildings," Building Acoustics, vol. 20, pp. 193–214, 02 2013

[10] Gover, B., Bradley, J., Schoenwald, S., Zeitler, B.: "Subjective ranking of footstep and low-frequency impact sounds on lightweight wood-framed floor assemblies," in Proceedings of Forum Acusticum, pp. 1–6, 01 2011

[11] Horvat, M., Benklewski, J., Jambrosˇic´, K., Müllner, H., Rychtarikova, M., Exel, R.: "The challenges in preparing the stimuli to be used in subjective evaluation of impact sound insulation," in Book of proceedings from ATF 2017 5th International Conference on Applied Technology, pp. 82–91, 2017

[12] Brinkman, W.-P. , Hoekstra, A. R., van, E. R.: "The effect of 3d audio and other audio techniques on virtual reality experience," Studies in health technology and informatics, vol. 219, pp. 44–48, 2015

[13] Koehl, V., Paquier, M., Delikaris-Manias, S.: "Comparison of subjective assessments from listening tests through headphones and loudspeaker setups," in 131st Audio Engineering Society Convention 2011, vol. 1, 10 2011

[14] Ivancevic, B.: Elektroakustika. Zagreb, Croatia: University of Zagreb, 3.2 ed., 2007

[15] Bech, S., Zacharov, N.: Perceptual Audio Evaluation - Theory, Method and Application. John Wiley and Sons, 11 2006

[16] Nawrocka, A., Holewa, K.: "The analysis of the different frequencies sound waves effect on the eeg signal," Solid State Phenomena, vol. 208, pp. 177–182, 1 2014

[17] Bhaskar, R., Choudhuri, R., Pandey, A., Bandopadhyay, S., Sarangi, S., Kumar Ghatak, S.: "Effect of rotating acoustic stimulus on heart rate variability in healthy adults," The open neurology journal, vol. 6, pp. 71–77, 2012

[18] Arteaga, D.: "Introduction to ambisonics," 2015. URL: https://www.researchgate.net/publication/280010078 accessed on August 25th 2019

[19] Horvat, M., Jambrosic, K., Domitrovic, H.: "Construction of an a uralization laboratory based on multichannel loudspeaker system," in Proceedings of the International Conference on Acoustics, (Berlin, Germany), p. p. 2356 2359, 2013

[20] Gerzon, M. A.: "General metatheory of auditory localisation," in Audio Engineering Society Convention 92, Mar 1992

[21] Malham, D.: "The early years of ambisonics at york," in Audio Engineering Society Conference: 2019 AES International Conference on Immersive and Interactive Audio, Mar 2019

[22] Stein, E., Goodwin, M.M.: "Ambisonics depth extensions for six degrees of freedom," in Audio Engineering Society Conference: 2019 AES international conference on headphone technology, Aug 2019

[23] Farina, A., Pinardi, D., Binelli, M., Ebri, M., Ebri, L.: "Virtual reality for subjective assessment of sound quality in cars," in Conference: AES 144th International Pro Audio Convention, (Milan, Italy), 05 2018

[24] Sherbourne, S.: "Ambisonics and vr/360 audio in pro tools — hd," 2017. URL: http://www.avidblogs.com/ambisonics-vr360--audio-pro-tools-hd/ accessed on August 25th 2019

[25] Frank, M., Sontacchi, A.: "Case study on ambisonics for multi-venue and multi-target concerts and broadcasts," Journal of the Audio Engineering Society, vol. 65, pp. 749–756, 09 2017

[26] Youtube, "Video upload requirements for spatial audio," 2019. URL: https://support.google.com/youtube/answer/6395969 accessed on August 25th 2019

[27] Google, "Resonance audio overview," 2019. URL: https://developers.google.com/resonanceaudio/develop/overview accessed on August 25th 2019

[28] Facebook, "Facebook 360 spatial audio workstation," 2019. URL: https://facebook360.fb.com/spatialworkstation/ accessed on August 25th 2019

[29] Adobe, "Support for vr workflows," 2019. URL: https://helpx.adobe.com/premierepro/using/VRSupport.html accessed on August 25th 2019
[30] Steinberg, "3d mixes for ambisonics," 2019. URL: https://steinberg.com accessed on August 25th 2019
[31] Cockos Inc., "Reaper digital audio workstation," 2019. URL: https://www.reaper.fm/ accessed on August 25th 2019
[32] Kronlachner, M.: "ambix v0.2.8 – ambisonic plugin suite," 2019. URL: http://www.matthiaskronlachner.com/?p=2015 accessed on August 25th 2019
[33] Blue Ripple Sound Limited, "A complete audio workflow for virtual reality," 2019. URL: http://www.blueripplesound.com/ accessed on August 25th 2019
[34] Audio Ease B.V., "Audioease 360 pan suite," 2019. URL: https://www.audioease.com/360/ accessed on August 25th 2019
[35] SPOOK, "Spooksyncvr for gopro vr player," 2019. URL: https://www.spook.fm/spooksyncvr/ accessed on August 25th 2019
[36] dearVR, "dearvr spatial connect: The future of audio production for vr and ar," 2019. URL: http://dearvr.com/ accessed on August 25th 2019
[37] Ian McAnally, K., Lance Martin, R.: "Sound localization with head movement: Implications for 3-d audio displays," Frontiers in neuroscience, vol. 8, p. 210, 08 2014
[38] McKeag, A., McGrath, D.S.: "Sound field format to binaural decoder with head tracking," in Audio Engineering Society Convention 6r, Aug 1996
[39] Heller, A., Lee, R., Benjamin, E.: "Is my decoder ambisonic?," in Audio Engineering Society Convention 125, Oct 2008
[40] Wiggins, B.: "The generation of panning laws for irregular speaker arrays using heuristic methods," in Audio Engineering Society Conference: 31st International Conference: New Directions in High Resolution Audio, Jun 2007
[41] Engel, I., Henry, C., Amengual Gar´ı, S., Robinson, P.W., Poirier-Quinot, D., Picinali, L.: "Perceptual comparison of ambisonics--based reverberation methods in binaural listening," in EAA Spatial Audio Signal Processing Symposium, (Paris, France), 2019
[42] Hodges, P.: "History of recording,". URL: https://ambisonic.info/history.html, 2017
[43] Lopez, M. J., Kearney, G.C., Hofstadter, K.: "Enhancing audio description: Sound design, spatialization and accessibility in film and television," in Reproduced Sound Conference, (Southampton, UK), 2016
[44] Wefers, F., Pelzer, S., Bomhardt, R., Müller-Trapet, M., Vorlaender, M.: "Audiotechnik des aixcave virtual reality-systems," in Conference: 41. Jahrestagung fu¨r Akustik (DAGA2015), (Nuremberg, Germany), 03 2015
[45] Whatis.com, "Head tracking," 2017. URL: https://whatis.techtarget.com/definition/head-tracking accessed on August 25th 2019
[46] Paquier, M., Koehl, V.: "Audibility of headphone positioning variability," 128th Audio Engineering Society Convention 2010, vol. 2, 05 2010
[47] Zacharov, N., Wickelmaier, F.: "Perceptual audio evaluation—theory, method and application," Journal of The Acoustical Society of America, vol. 122, 07 2007
[48] De Man, B., Jillings, N., Moffat, D., Reiss, J., Stables, R.: "Subjective comparison of music production practices using the web audio evaluation tool," in Conference: 2nd AES Workshop on Intelligent Music Production, 09 2016
[49] ITU-T, Recommendation ITU-T P. 800: Methods for subjective determination of transmission quality. International Telecommunication Union, 1996
[50] ITU-R, Recommendation ITU-R BS. 1116-1: Methods for the subjective assessment of small impairments in audio systems including multichannel sound systems. International Telecommunication Union, 1997
[51] ITU-R, Recommendation ITU-R BS.1534-1: Method for the subjective assessment of intermediate quality levels of coding systems. International Telecommunication Union, 2003
[52] Jillings, N., De Man, B., Moffat, D., Reiss, J.: "Web audio evaluation tool: A framework for subjective assessment of audio," in Conference: Proc. 2nd Web Audio ConferenceAt: Atlanta, Georgia, USA, 04 2016
[53] Lee, H.: "Toward the development of a universal listening test interface generator in max," in AES Convention 138, 2015
[54] Jillings, N., Moffat, D., De Man, B., Reiss, J.: "Web audio evaluation tool: A browser-based listening test environment," in 12th Sound and Music Computing conference, 07 2015
[55] Ciba, S., Wlodarski, A., Maempel, H.-J.: "Whisper – a new tool for performing listening tests," 126th Audio Engineering Society Convention 2009, vol. 1, 01 2012
[56] De Man, B., Reiss, J.: "Ape: Audio perceptual evaluation toolbox for matlab," in 136th Convention ofthe AES, 04 2014
[57] Giner, A.V.: "Scale - a software tool for listening experiments," in AIA/DAGA Conference on Acoustics, 2013
[58] Vincent, E., Jafari, M.G., Plumbley, M.: "Preliminary guidelines for subjective evaluation of audio source separation algorithms," in ICA Research Network Workshop, 04 2012
[59] Kraft, S., Zölzer, U.: "Beaqlejs: Html5 and javascript based framework for the subjective evaluation of audio quality," in Linux Audio Conference, 05 2014
[60] A. R. Lab, "Step - subjective training and evaluation program," 2019. URL: https://www.audioresearchlabs.com/arl-step/ accessed on August 25th 2019
[61] Schoeffler, M., Bartoschek, S., Stöter, F.-R., Roess, M., Westphal, S., Edler, B., Herre, J.: "webmushra — a comprehensive framework for web-based listening tests," Journal of Open Research Software, vol. 6, 02 2018
[62] Hynninen, J., Zacharov, N.: "Guineapig – a generic subjective test system for multichannel audio". 2012. URL: https://www.researchgate.net/publication/229045731 accessed on August 25th 2019
[63] COST Action TU0901, Building acoustics throughout Europe Volume 2: Housing and construction types country by country. DiScript Preimpresion, S. L., 2014

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