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TRENDS IN THE USE OF VIRTUAL REALITY FOR ACOUSTIC INVESTIGATION OF THE BUILT ENVIRONMENT

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ABSTRACT

Virtual Reality (VR) in combination with auralization methods has emerged as a powerful tool for assessment and optimization of acoustics within the built environment by enabling instant design modifications, accelerated testing, and flexibility in comparing design variations. The technology allows the integration of visual stimuli, when participants explore soundscapes and evaluate different acoustic properties, such as reverberation, noise levels, and speech intelligibility. This paper investigates the various applications of VR in this domain, drawing upon literature from the past 10 years. The technology is demonstrating its maturity, with numerous studies already validating the methodological approach using VR. Its most common applications in acoustics research are in 1) design and evaluation of acoustic environments, including simulating different acoustic treatments and evaluating the impact of design changes, and 2) investigating human perception and response to sound, such as assessing the impact of various acoustic environments on the user's experience. This paper highlights the growing potential of VR as a tool for investigating acoustic comfort and functionality of the built environment.

Keywords: *virtual reality, auralization, validation studies, sensory congruence.*

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1. INTRODUCTION

The use of acoustic virtual reality (AVR) technologies within the built environment encompasses the two major fields of acoustics, room acoustics and building acoustics. The predominant area of application of acoustic investigation within the built environment has broadened from traditional optimization of concert halls and performance spaces to general sound perception and noise control in everyday environments [1]. As such, expanding the area of application of AVR methods alike.

Acoustics requirements can be challenging to comprehend while at the same time measures to achieve optimal acoustic conditions need to be well balanced. As such, acousticians must often compare the effects of different acoustic interventions in the physical space which can be expensive, time-consuming, and impractical. Instead, a shift to utilizing simulations of acoustic environments in combination with AVR represents an economically and all-around more efficient alternative, potentially reducing the resource demands associated with traditional physical prototyping and in-situ testing. In recent years of rapid development of AVR technology, many acousticians have begun to rely on acoustic simulations for optimized room design in terms of room acoustics [2]. To take a step further in optimizing the design process, virtual visual environments have been integrated into acoustic simulations or auralizations. This multi-sensory approach, leaning on the interplay of visual and auditory elements, allows for adopting holistic design approaches that have not been possible to implement before. The numerous studies conducted in recent years have demonstrated the potential of AVR to be applied to investigating various diverse and multifaceted acoustic challenges.

The purpose of this paper is to illustrate recent applications of AVR technologies in research and the trends we can expect to see moving forward. The paper is structured as follows:

i. a brief overview of the origin and development of AVR and auralization is provided,
ii. the most common applications of AVR are illustrated in the form of a list of validity and exemplary studies from the field of perceptual room acoustics,
iii. expected trends and directions of further uses are presented.

A handful of exemplary studies were selected for demonstration based on 1) the approach they adopted in validating AVR as a tool for acoustic investigations and 2) the acoustic parameters that were investigated by means of implementing AVR technology.

2. ORIGIN AND DEVELOPMENT OF AURALIZATION AND AVR

Please compress images and figures as necessary before submitting. Considering room acoustics, computer simulations first emerged in the 1960s when the first scientific article was published in 1968 on the topic of acoustical room response by means of ray tracing [3]. Through fast development of the computer industry in the second half of the 20th century, acoustic modeling and simulation experienced great advances as well. With the start of the 1990s, even personal computers reached a point when they were powerful enough to run room acoustics software that became commercially available [4, 5]. Since then, acousticians and designers have continually utilized computer simulations for optimization of acoustics within the built environment. The two main types of approaches for conducting room acoustics simulations that have been around a long time and have set a foundation to build upon towards auralization and later AVR are 1) geometrical acoustics approach and 2) wave-based acoustics approach [6,7]. Modern simulation tools tend to combine both approaches in a hybrid method for most accurate and efficient sound modeling [8]. The input data for such simulations are typically architectural characteristics of the investigated space, such as acoustic properties of surface material, room volume, and surface areas [1]. The typical outputs from room acoustic simulations are quantified acoustic parameters (e.g. reverberation time, clarity, and strength) and the impulse response of a room often shortened to RIR. These simulations, while providing valuable quantitative data, form the essential foundation for auralization, which goes beyond numerical results to create an immersive auditory experience.

Auralization could be considered as the acoustic counterpart to visualizations. It is defined by Kleiner et al. as the creation of a rendered audible sound field of a sound source within a space through utilizing physical or mathematical modeling to simulate a binaural listening experience at any given position [9]. Auralization was a giant leap forward to AVR. While the two are essentially similar in what they aim to achieve, the biggest difference is in source and receiver localization. A considerable limitation of traditional auralization is the lack of dynamic movement and head tracking it provides. AVR requires the receiver to move in the space that might also contain dynamic sound sources [10]. With the recent rapid advancement in the VR technology industry, static auralizations can be expected to lose their relevance [11]. To further advance the architectural design process, there has been an addition of immersive visual components to the AVR by novel virtual reality technology, often by means of a head mounted display. This allows for the user of the technology to be exposed to auditory and visual stimuli concurrently, increasing the immersion experience as the two senses enhance each other. Through multi-sensory exposure, the technology allows for more holistic design practices. An example of such an approach would be experimental assessment of how the visual components of building materials affect the perception of room acoustics.

3. VALIDATION OF AVR TECHNOLOGIES

Simulating realistic virtual sound environments is much more challenging than creating their visual counterparts. The main goal is combining both aspects to create an ecologically realistic immersive experience for the user. As such, when applying AVR technologies and using acoustic virtual environments it is imperative to determine the quality of the reproduction system and consequently the ecological validity of the environment in which the user is immersed. Despite the use of AVR becoming a staple, the technology still poses some uncertainties associated with perceptual discrepancies. Two main factors influencing perceived immersion related to acoustics are sound source localization and room impression [12]. Main identified discrepancies include the absence of interactions with other senses such as physical touch, smell, or temperature sensing. Additionally, with the use of VR through head mounted displays some side effects could present themselves during or after immersion, such as cyber sickness or motion sickness [13]. The term commonly used in discussions related to ecological validity of VR spaces is *congruence*. It can be defined as "powerful similarity between perceptual variables and in processing of physical and semantic information" [13].

The reviewed literature on the validation of AVR is structurally presented based on the motivation and the field of research it has been conducted in. The key findings are summarized in Table 1.

3.1 Acoustic and visual congruence

There have been several studies that have demonstrated strong potential of VR as a tool to create a plausible virtual world. A validity study conducted by Luigi Maffei et al. (2016) was one of the first to aim to understand acoustic and visual congruence of simulated versus real world. The researchers hypothesized that the coherence, familiarity, and congruence between corresponding acoustic and visual elements should be substantially similar in both groups: the sample of participants was divided into two groups, one exposed to the environment in-situ and one exposed to the environment in a laboratory setting [13]. After exposure they responded to questionnaires on a 7-point Likert scale evaluating:

- Global environmental quality,
- Acoustic coherence and familiarity,
- Visual coherence and familiarity,
- Salience of acoustic sources and visual elements.

For the laboratory setting exposure, sound was recorded during the in-situ experiment and reproduced through a playback system of 5 loudspeakers placed in an anechoic chamber. The visual part was presented through a head mounted display. The duration of the laboratory experiment was approximately 10 minutes. The results showed robust similarities in subjective evaluations in all examined categories between responses of in-situ participants and laboratory participants.

This study serves as an example of methodology on how to conduct research on ecological validity of immersive virtual environments in outdoor urban settings. The methodology used in the study stresses the importance of assessing acoustic and visual environmental quality on their own as well as assessing them integrated in a global environment. Additionally, the results of the study show that VR technology already available almost a decade ago (2016) has reached sensory congruence levels needed.

3.2 Sound insulation and speech intelligibility

There An exemplary study conducted by Imran Muhammad et al. (2019) [14] is significant for its aim to reproduce results of a previous study of the effect of different background speech conditions on cognitive performance (Schlittmeier et al. [15]), using a new approach with implementation of audio-video VR. The study serves as a bridge between VR validity studies and the methodology of applying VR to psychoacoustic studies. The research question posed was whether the results of noise effect patterns originally obtained in a real laboratory listening experiment [15] could be reproduced in an audio-video rendered VR office environment. The building acoustics parameter that the study controlled was sound insulation at different levels which lead to different speech intelligibility levels in the receiving room.

The VR experiment was conducted using a head mounted display; the virtual scene of an office environment was created in Unity 3D software, a common VR developer tool utilized in multiple AVR experiments [11, 16, 17, 18]. Participants were placed in a virtual office environment and tasked with a cognitive performance test. The test used was a serial digit recall, a standardized procedure to measure short-term memory. The test was incorporated into the Virtual Reality scene on a virtual computer screen within the virtual office. The only tangible real world component used was a computer mouse with which the participants controlled the virtual computer's display.

The study confirmed that the sound-related effects on cognitive performance were consistent between the audio-video VR environment and a real-world laboratory setup with the same speech conditions. This study was the first to provide significant evidence and prove the validity of audio-video VR as an efficient tool for assessing building acoustics' impact on cognitive and subjective responses [14]. This study has been highly influential, with numerous subsequent studies building upon its methodology or citing its validation of the approach.

3.3 Ambient Noise and Reverberation Time

A recent study by Rachel Dogget et al. [17] employed VR for investigating the impact of room acoustics on well-being and cognitive performance while aiming to validate the use of VR as a tool for such research. In the study, reverberation time was the manipulated room acoustics parameter through acoustic treatment with sound-absorbing materials, directly influencing the resulting ambient noise level. The researchers hypothesized a negative impact of irrelevant ambient noise on cognitive performance, mood, and well-being measured by physiological responses, and mainly that the simulated acoustic intervention would mitigate the above impacts [17].

The technology adopted for the experiment was a head mounted display with a 360-degree view and 6 degrees of freedom, and stereo headphones, for which the ambisonics sound was decoded. The visual virtual environment was created with the use of the Unity 3D. The cognitive performance test of choice was the standardized n-back stimulus recall test, assessing working memory, that was administered in an auditory version due to the participant wearing a VR headset. Physiological measures of stress were assessed through skin conductivity level, heart rate, and heart rate variability. The mood of participants was assessed through a verbally administered subjective questionnaire. The participants were immersed into three different virtual environments, one with no ambient noise, one with ambient noise with no acoustic treatment, and one with ambient noise manipulated by acoustic treatment.

The study demonstrated that ambient noise negatively impacted cognitive performance, regardless of working-memory load, and that reducing reverberation through simulated acoustic interventions mitigated these effects. However, physiological measures and mood remained unaffected by both background noise and the simulated room acoustics. A note-worthy limitation of the study is the lack of direct comparison of the virtual classroom environment with the real-life one to confirm validity of results. However, earlier work has successfully shown cognitive changes in virtual environments [14]. The study concludes that high-fidelity VR simulations enable efficient acoustic intervention evaluation, fostering optimal performance and well-being in built environments [17].

3.4 Soundscape immersion

An example of visual and acoustic virtual reality being used complementary within the built environment is for exploring museums and exhibitions. To investigate the additional immersion that soundscape design offers, Joran Rudi [18] conducted a study on the potential of sound in shaping visitor experiences within a virtual environment designed for an architectural museum exhibition. The study specifically investigated how auditory elements contribute to the sense of presence and realism in VR settings.

The participants in the study were exposed to a virtual reality environment of a contemporary villa interior, through a head-mounted display. Sounds were reproduced via a combination of loudspeakers and an open headset, utilizing various techniques for 3D acoustic modeling and dynamic sound projection [18]. The AVR system included a motion-tracking system to account for changes in position and rotation. After their experience, the 82 participants were interviewed to assess their experiences of realism in the soundscape and how this contributed to their immersive experience, specifically the perception of realism in sound, impact of sound on immersion, appropriateness and variation of sounds, and technical quality and delivery methods [18].

The study found that sounds contributed heavily to a high degree of immersion. Participants reported that soundscapes significantly enhanced the realism of the virtual environments, noting that appropriate and varied sound signals and sound types were crucial in achieving this heightened realism. Issues related to sound quality and delivery methods showed minimal impact on the visitor experience, suggesting that while technical aspects are important, the contextual appropriateness of the sound design plays a larger role in enhancing immersion.

The finding of the study confirmed sound, specifically thoughtful soundscape design, is a crucial element in creating a realistic and immersive experience in VR exhibitions. It is also suggested that to maximize the effectiveness of VR experiences, designers should prioritize the development of well-integrated and dynamic soundscapes that complement visual elements. By applying these principles, VR environments can achieve greater sensory engagement, resulting in more immersive and compelling user experiences.

Table 1. Summary of the overviewed studies validating AVR technologies, listed based on the research motivation in the specific field of acoustics. Each study is summarized based on its most relevant findings.

Ecological Validity & Perceptual Congruence	
Maffei et al. (2016) [13]	Found high sensory congruence between visual and auditory elements in real-world vs. VR environments.

Colsman et al. (2016) [12]	Developed an immersion questionnaire to assess AVR's accuracy in replicating real-world acoustics.
Reproducibility of Psychoacoustic Experiments	
Muhammad et al. (2019) [14]	Demonstrated AVR's reliability in reproducing cognitive effects of noise in controlled lab settings.
Doggett et al. (2021) [17]	Showed AVR's effectiveness in evaluating the impact of reverberation and ambient noise on cognitive performance and well-being.
Technical Accuracy & Spatial Sound Perception	
Ballestero et al. (2017) [11]	Showed that head-tracked auralization is important to improve dynamic spatial audio experiences in VR.
Pind et al. (2018) [2]	Highlighted computational challenges and trade-offs between accuracy and real-time processing in AVR.
Applications in Architectural & Acoustic Design	
Milo & Hornikx (2021) [16]	Used AVR as an educational tool for built environment students to explore the effect of acoustic treatment in real-time.
Rudi (2021) [18]	Studied AVR's role in museum and exhibition soundscape design, proving its impact on user immersion. It has been shown that contextual appropriateness is highly relevant for the immersion experience.

4. DISCUSSION ON THE POTENTIAL FUTURE AVR APPLICATIONS

AVR technology can be expected to advance in terms of technical performance, becoming lighter and thus more 'wearable.' We cannot predict whether cybersickness and other related issues will be eliminated, but the hardware will certainly become increasingly commercially accessible, leading to its wider adoption and use in new and unforeseen ways.

Given the growing body of research validating the use of AVR in acoustic investigations, a decline in studies primarily focused on AVR validation within the acoustic scientific community can be anticipated. As technology continues to evolve, enhancing both ecological validity and sensory congruence, further validation studies may become increasingly redundant. Future research is likely to shift towards investigations that directly address primary research questions, leveraging the validation established by previous studies. Furthermore, advancements in VR technology are expected to drive a transition within the field of acoustic simulations and modeling, with AVR progressively replacing traditional static auralizations for assessing existing or future designs [2]. Future applications of this technology could also include virtual reconstructions of historical spaces no longer physically existing and other applications in archaeological context [11].

However, despite its advancements, it should be mentioned that the technology still faces some limitations for its use in research and design applications. One major challenge is modeling complex sound behaviors, particularly in environments with multiple dynamic sound sources and acoustic interactions. Real-time auralization requires much computational power to accurately simulate sound propagation, reflections, and diffractions, often leading to trade-offs between accuracy and system performance [1, 2]. Another challenge are the limitations of head-tracking accuracy and spatial audio reproduction can affect the perceived realism of virtual acoustic environments, particularly when using standard consumer-grade VR hardware [11]. Furthermore, while AVR can replicate spatial and temporal acoustic properties, it often lacks integration with other sensory modalities such as haptics, which could enhance overall immersion [12]. Addressing these technical and perceptual challenges will be beneficial for refining AVR as a reliable technology.

For pedagogic purposes, AVR also holds significant potential, particularly within the field of built environment education. By providing immersive experiences, AVR can effectively demonstrate acoustic design principles to students. For instance, Milo & Hornikx from Eindhoven University of Technology have recently developed an AVR platform that allows students to experiment with different combinations of acoustic materials and room sizes and to listen to the resulting acoustic changes in real-time [16]. This type of interactive learning can enhance understanding and engagement, making AVR a valuable tool for acoustic education.

The significant expansion in the identified applications of AVR by the scientific community suggests a potential substantial increase in its implementation within industry, particularly in room and building acoustic design and architectural design. One of the directions where utilization of AVR technologies has immense potential is in stakeholder engagement and involvement in the design process. There are often many people involved in the building design process, however they tend to have various levels of architectural or engineering background, if any at all. The use of VR promotes inclusivity in decision-making and participatory planning as it expands the pool of people able to interpret design plans through immersive models and not only architectural plans [13].

5. CONCLUSION

This paper has explored the evolution, applications, and recent trends in utilization of AVR for the purpose of investigating acoustics within built environments. It has been shown that by enabling rapid design modifications, accelerated testing, and flexible comparisons, AVR functions as a powerful tool for the assessment and optimization of acoustic design. The review of recent studies demonstrates AVR's effectiveness in diverse areas of study, including the design and evaluation of acoustic environments and the investigation of human sound perception. Notably, research has validated AVR's capacity to reproduce real-world acoustic phenomena and accurately assess the impact of acoustic parameters such as speech intelligibility, reverberation time, and ambient noise on cognitive performance. The integration of visual components with AVR aids in creating immersive, multi-sensory experiences which further enhance its utility and promote holistic design practices. While current limitations such as challenges in modeling complex sound behaviors and computational demands exist, ongoing technological advancements are bound to refine AVR, solidifying its role in shaping future acoustic environments and transforming acoustic design and evaluation.

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