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VIRTUAL REALITY APPLICATIONS IN URBAN SOUNDSCAPE ASSESSMENT: AN OVERVIEW

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ABSTRACT*

Investigating soundscapes in urban environments is fundamentally dependent on environmental factors. Due to the complex nature of the urban environment and uncontrollable factors, conducting these studies is challenging. Virtual reality (VR) allows urban soundscapes to be studied in a controlled laboratory environment, enabling more predictive assessments. VR, multi-sensory perception environments, and immersive experiences provide a better assessment of the urban problem. These studies can have a significant impact on design choices in urban environments, as well as provide the opportunity to experience the design decision in advance. This study aims to provide an overview of urban acoustic experiments performed with virtual reality technology and explores its application in analyzing urban soundscapes. To achieve this, this study first classifies urban soundscapes investigated using VR. This classification is organized based on the various urban area selections and the objectives of the analyzed studies. The relationship between the urban soundscape and the performance of VR is discussed. It then provides perspectives on the current challenges of using VR to assess the soundscape in urban environments. Finally, the study offers insights into the current challenges, opportunities, advantages, and limitations of utilizing VR for soundscape assessment in urban contexts.

Keywords: *Virtual reality; Urban soundscape; Audiovisual*.

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1. INTRODUCTION

Environmental noise is one of the major problems facing cities. It is a significant public health concern and ranks among the most significant environmental hazards to human health. Research on environmental noise focuses on improving the quality of urban life and enhancing the functionality of pleasant urban acoustic environments. However, conducting studies on urban acoustics, including both design decisions, is challenging because of the multifaceted characteristics of urban environments. Technology has made the widespread implementation of thorough investigations that consider various urban elements easier. Consequently, advanced tools like VR are increasingly being integrated into urban studies to enhance the simulation and analysis of these elements. **Virtual reality** technology is growing as an important instrument for urban acoustic studies[1]. Virtual reality is used to see the possible consequences of the urban decisions to be taken. In VR, different approaches can be tried, and studies focusing on user perceptions can be carried out. The determination of citizens' perceptions of urban problems, as well as their levels of pleasantness or discomfort, is critical for large-scale and costly urban studies. The design of significant areas like highways, urban green spaces, and historical areas incorporates VR. These studies actively utilize user perception to enhance the intelligence, environmental friendliness, and sustainability of cities[2].
Advances in technology have made virtual environment representations increasingly lifelike. This development is evident in the growing body of research conducted recently. Despite the growing number of VR studies conducted in urban areas, there is a gap in the systematic review of existing publications on the evaluation and design of urban acoustics that incorporate audiovisual elements. Therefore, this study aims to assess existing research methods, audiovisual elements, and VR studies in urban areas. Therefore, this study focused on analyzing VR studies that integrate both visual and audio features and specifically

explore urban environments. As a result, this study provides guidelines and recommendations for the field of VR studies in urban environments. This assessment offers a more profound understanding of the urban acoustic studies in VR and provides significant data for future research.

2. METHOD

This investigation follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic reviews. Relevant papers were selected from Scopus, Web of Science, and Google Scholar. The search query consisted of the following keywords: "virtual reality" + "soundscape." By 31 December 2024, various searching databases identified a total of N = 1297 candidate papers. This study is confined to the last five years to narrow the focus of the study. Initially, overlapping research, book chapters, conference proceedings, review, and bibliometric review research were excluded from the sources obtained in the investigation. The selected studies were intended to concentrate especially on soundscapes and use virtual reality technologies for visual and audio representation. Consequently, indoor studies and studies employing virtual reality technology only for auditory or visual purposes were excluded from this research. The studies were intended to include both visual and audio features. This study examined VR research carried out in outdoor settings, specifically urban environments. The study included 49 unique papers.

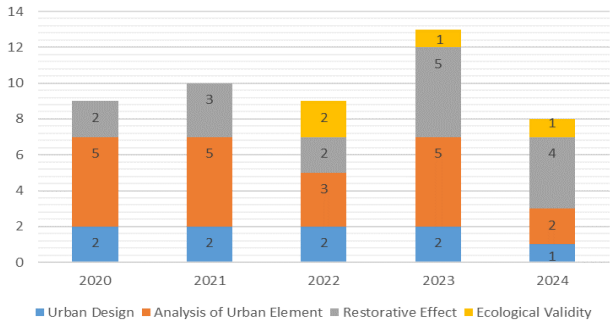

Figure 1. Selected research according to years and research goals. (N = 49)

The selected literature for the study was categorized into two main groups: (1) research goals, and (2) field selections. Studies are classified into four categories, and the relevant research is analyzed within these classifications. The first category is urban planning and design, the second is analysis of urban elements, the third theme is ecological validity, and the last theme is restorative effect. Figure 1 shows studies by year and the distribution of these categories.

Due to the page limit of this paper, not all reviewed studies are individually cited. Instead, this study provides a general framework by synthesizing key findings and trends observed in the literature. The references included represent a selection of the most relevant and representative works that support the discussion and conclusions.

3. RESEARCH GOALS

3.1 Urban Planning and Design

VR is a crucial tool in urban design, allowing planners and stakeholders to experience large-scale planning and development projects in a virtual environment. VR is increasingly used in urban planning and design. This technology makes planning processes more dynamic, making them more accessible and understandable for both experts and the public. VR allows users to realistically experience different urban design scenarios and contributes to decision-making processes.Engel et al. [3] created a VR-based project using 3D modeling. By experiencing different design scenarios in a virtual environment, participants were able to provide better-informed feedback on urban planning decisions. Echevarria Sanchez et al. [4] evaluated future regeneration alternatives for the design of urban public areas using VR. They showed that the auditory environment had a statistically significant impact on the overall level of pleasantness. The study provides comprehensive data on the relationship between audiovisual elements.

Conventional planning methodologies allow limited public engagement in the process. Nonetheless, VR facilitates digital democracy by enabling public participation in the design process. Individuals can engage in the planning process, offer comments, and enhance their comprehension of spatial decisions through web-based and virtual participatory technologies. Meenar et al. [5] investigated the application of VR in participatory planning, analyzing the potential for enhanced public engagement in planning processes within a virtual context. Yanaky et al. [6] introduced a VR-based soundscape design tool named "City Ditty," with a user-centered design methodology. This tool allowed users to actively participate in the process of spatial planning.

VR-based assessment methods are becoming increasingly common in urban planning and environmental analysis. As an alternative to traditional field studies, the methodologies aim to simulate user experiences in a virtual environment

and compare them with real-world perceptions. Dongas et al. [7] introduced the "Virtual Urban Field Studies (VUFS)" system for application in urban research. The research examined human-computer interaction with VR. Belaroussi et al. [8] developed a high-resolution three-dimensional model of an urban area utilizing Building Information Modeling (BIM) and Geographic Information System (GIS) data, and assessed user impressions within a virtual environment.

Current literature indicates that VR is a mechanism that bolsters stakeholder engagement in urban design, improves spatial awareness, and increases transparency in urban planning. Nevertheless, elements like technological constraints, deficiencies in user experience, and the necessary infrastructure for extensive adoption indicate that advancements in this domain require additional enhancement.

3.2 Analysis of Urban Element

The advancement of VR incorporating auditory and visual elements in urban settings is a relatively new development. Therefore, a significant amount of research in this field concentrates on analyzing the impact of diverse audiovisual elements on individuals' perceptions. Research on audio-visual interaction has concentrated on understanding the interrelationship between visual and aural elements. Jo and Jeon [9] investigated the impact of audiovisual stimulation in various urban environments. They discovered that the visual information had a 76% impact on total satisfaction, while auditory information had a lower impact of 24%. Zhou et al. [10] demonstrated a strong correlation among contentment with green spaces, environmental cleanliness, architectural aesthetics, and soundscape assessment. Lu et al. [11] examined audio-visual perception in urban areas. Analyzed audiovisual interaction by categorizing visual features based on indices like the “Green View Index” (GVI). The results indicated that green spaces increase the perception of pleasantness when traffic density is low.

Many studies have found that green spaces, water features and natural sounds improve urban acoustic perception. Puyana-Romero et al. [12] showed that environments with water sounds are perceived as more pleasant. Hong et al.[13] examined the effect of the distance between water sound and traffic noise on perceived soundscape quality and found that water sound plays a critical role in noise masking. Jo and Jeon [14] found that birdsong enhances the perception of pleasantness in green spaces and that human activity affects park dynamics.

Research occurs on environmental noise within VR, wherein sound sources like helicopters, aircraft, and wind turbines are simulated, and user perception is examined. Puyana-Romero et al. [15] discovered that removing helicopter noise made the soundscape more pleasant; the elimination of helicopter noise enhanced the auditory environment. Methodological studies also investigate the soundscape of urban areas in VR. Jo and Jeon [16] assess the effectiveness of the soundscape approach. The data acquisition methods outlined in ISO 12913-2 for soundscape studies were replicated. Hong et al. [17] investigated the influence of sound recording technologies on human perception, demonstrating how various systems affect perception.

VR has grown into a significant tool in urban design and environmental perception research. VR studies enhance comprehension of multisensory perception in urban environments and aid in formulating focus on users and sensory-optimized design methodologies. Subsequent study needs to investigate audio-visual interaction more comprehensively using larger datasets that encompass diverse user demographics.

3.3 Ecological Validity

Ecological validity has come to be a crucial topic for current VR research. It indicates the level to which the findings of a controlled laboratory experiment are relevant to real-world situations [18]. The laboratory should closely imitate real-world settings when considering the context of the questioning being asked. Ecological validity is an essential component of the validity of research conducted in VR. The restricted immersion experienced in laboratories may lead to diminished ecological validity, thereby limiting the generalizability of the results obtained.

In urban studies, standard laboratory-based experiments offer control over experimental circumstances or components; nevertheless, they frequently lack ecological validity as a result of the absence of real-world context. By contrast, on-site studies like surveys, soundwalks, or interviews can preserve context but are unable to control variables [19]. For this reason, ecological validity is consistently the major topic of research in urban virtual reality that is undertaken with various methodologies, technologies, and contexts.

Research on ecological validity in urban areas has started with the use of IVR technology. The extensive utilization of computer-aided design (CAD), visualization tools such as 360-degree cameras, and graphic display technologies has facilitated these studies. Upon reviewing the research in this field, the initial studies focus on comparing questionnaires conducted in IVR to real-world settings. Maffei et al. [20], Puyana-Romero et al. [21] and Hong et al. [17] conducted

their research in virtual and real environments. Their questionnaires included several inquiries regarding auditory and visual elements, and participants' overall evaluations of environmental quality, pleasantness, tranquility, and vibrancy were compared. In the results, there are no statistically significant variations in the outcomes of their questionnaire. Furthermore, in the real world and the IVR, there is research that investigates the distinctiveness of various virtual audiovisual environments concerning reproducibility. Gök Tokgöz and Altinsoy [22] conducted a comparison between a multimodal laboratory setting and a real-world environment utilizing a soundscape questionnaire, revealing no significant difference in results. Yang et al. [19] conducted a comparative analysis of diverse technologies employed in the creation and reproduction of VR. These technologies encompass field recording, virtual reality, augmented reality, and audio-only presentations. Upon conclusion of the study, the in situ evaluations provided higher pleasantness scores than all other methodologies. The selection of audio-visual reproduction technique had no substantial effect on the assessments. Ünal et al. [23] examined the validity of their questionnaire's restorative effect in real and virtual environments. They discovered that there were no significant differences between the real and virtual gardens in terms of perceived restorative characteristics.

Ecological validity is crucial in VR research, as it ensures reliable conclusions within each study's dynamics. High-realism virtual settings can be valuable for future research, but achieving this realism in complex subjects like urban areas can be challenging. Therefore, it is essential to increase research in this domain and establish ecologically valid measures that align with study objectives.

3.4 Restorative Effect

Several disciplines that examine the physical changes of the acoustic environment and the effects of these changes on individuals are changing their approaches. They are moving away from focusing only on negative aspects like pollution and harmful effects and instead adopting a more positive approach that uses multiple disciplines such as restoration and well-being [24]. Examining the restorative effect of a virtual environment is crucial for individuals who may derive the benefits of natural settings due to illness or various disadvantages.

By analyzing the restorative effects and studies on VR, the subjects can be categorized into four primary themes. The initial theme encompasses the analysis of restorative effects and VR environments, alongside the evaluation of fundamental measurement techniques. The second theme is the investigation of natural audiovisual elements. The third theme involves the examination of diverse technologies, while the fourth theme focuses on the assessment of individual differences.

The research **in the first theme** investigates the specific circumstances and mechanisms in which the restorative effect is pronounced in virtual environments. The restorative effect is perceived both visually and auraly [25]. Consequently, the investigation of natural visual and aural elements that have a restorative effect in the virtual setting is significant. Annerstedt et al. [26] investigated the effect of nature sounds on stress recovery in VR. It indicates a possible connection between natural environments, natural sounds, and stress recovery. Park et al. [27], Mioni and Pazzaglia [28], and Kawai et al. [29] demonstrated that green spaces possess a greater restorative impact relative to urban environments.

The second theme focuses on the change of natural audiovisual components in VR and their restorative effect. In terms of visual elements, studies have focused on the amount of greenery and the green-blue ratio. For auditory components, attention has been given to restorative natural sounds such as birdsong and water sounds. Masullo et al. [30] found that the presence of green and blue elements enhances our auditory perception and enhances the restorative effect. Jeon et al. [31] conducted a comprehensive VR experiment comparing the restorative effects of urban, waterfront, and green environments, concluding that waterfront areas provide the highest restorative benefits. Meng et al. [32] and Ha and Kim [33] investigated the role of biodiversity in restoration, emphasizing that ecologically rich environments contribute to stress recovery and that the visual presence of biodiversity enhances the restorative impact. Regarding auditory aspects, Goa et al. [34] examined the effects of water span and building height on restorativeness. Their findings indicate that incorporating birdsong in high-rise waterfront environments provides greater restorative benefits compared to stream sounds.

The third theme examines the revitalizing effects attained through the application of diverse technologies, multimodal approaches, and theoretical frameworks. Chen et al. [35] evaluated the restorative effect of green areas in the Cave Automated Virtual Environment (CAVE). The restorative effect was also observed in the CAVE. Kari et al. [36] tested the impact of three distinct environments (HMD, monitor, and a virtual room) on restoration and stress levels. There were no statistically significant changes seen between the HMD and virtual room.

The last theme emphasizes individual differences. The restorative benefits may vary according to distinct

personality qualities, cultural backgrounds, or age demographics. Senese et al. [37] analyze the multisensory immersive VR to examine the impact of personality traits and water masking installations on the perceived restorativeness of urban parks. They found that water installations increased fascination and being away, but personality traits can reduce this effect. Bazrafshan et al. [38] investigated the effect of personality traits on relaxation in urban parks. They found that personality traits and familiarity with urban parks significantly impact emotional responses, particularly relaxation. Long et al. [39] examined restorative effects on the elderly individuals residing in nursing homes. In their study, they found that silent videos evoked loneliness and isolation, suggesting audio plays a crucial role in this effect.

4. FİELD SELECTIONS

The study reveals considerable diversity in field selections. Despite comprehensive research across all fields, there is a pronounced emphasis on specific locales, such as green areas or roadsides. Thus, the field selection comprised two primary categories: green areas and transit corridors. The other group, referred to as other urban areas, includes diverse categories such as public spaces, residential zones, and historical sites. Figure 2 shows the field selections according to the research goals. The figure has been prepared by taking into consideration that some studies selected more than one field.

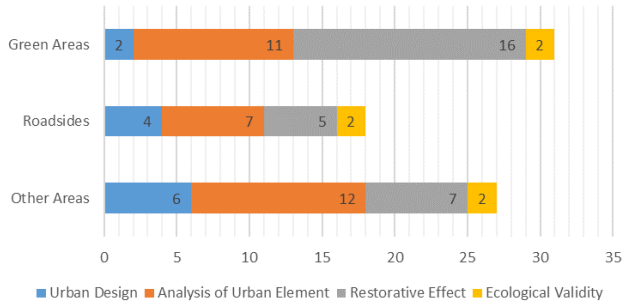

Figure 2. Relationships between research goals and field selection

A brief evaluation of field selections revealed that most research on the restorative effect takes place in green areas. These findings highlight the research focus on green areas, particularly in studies examining the restorative effect. This focus corresponds with the recognized advantages of natural surroundings for improving well-being. On the other hand, urban planning and design studies demonstrate a broader distribution across different urban settings, reflecting the need for diverse spatial analyses. The allocation of research concerning ecological validity and the analyses of urban elements are more balanced. They are suggesting a comprehensive approach to understanding both natural and built environments. This distribution emphasizes the need to extend research outside well-known domains to reach a more complete understanding of urban soundscapes and their influence on users.

5. DISCUSSION

The research goals and field selections in this study guided its classification. **Urban design and planning:** The use of VR facilitates communication between decision-makers by increasing public participation while enabling more informed decisions. However, an analysis of the studies in this field reveals a lack of comprehensive research on urban acoustics. **Analysis of urban elements** aims to understand the interaction between visual and auditory elements. These studies focus on important criteria such as the digitalization of urban areas and changes in user perception. **Ecological validity** is important to understand the compatibility of the virtual environment with reality. Areas with different visual and auditory characteristics should be studied with different laboratory conditions and data collection methods. Research examining **the restorative effect** is particularly important in the fields of health and psychology. Due to the growing population and spatial limitations, it is becoming difficult to create tranquil areas in cities. VR can be especially useful for disadvantaged groups such as the elderly and the disabled.

Field selection: Urban green areas are a priority research area; research on acoustically problematic areas, such as high-traffic areas, should be increased. Extending the studies to different urban environments will contribute to a more comprehensive understanding of the urban soundscape.

One of the **greatest challenges** in VR-based urban acoustics research is to design experiments with high ecological validity. Accurately representing the complex structure of cities visually and aurally is challenging, and factors such as participants' experiences and memory effects can influence the results. Furthermore, HMDs are the most commonly used visual devices in studies; their lack of user-friendliness makes it difficult to include older participants. Similarly, online surveys predominantly attract younger individuals, leading to demographic representation issues.

Future advancements in software, hardware, artificial intelligence, and mixed reality will enhance the realism, interactivity, and accessibility of urban VR research. Advanced HMD, haptic feedback, and multimodal experiences will augment the realism of virtual environments. Moreover, artificial intelligence and machine learning will enhance user experiences through the personalization of VR. The combined use of mixed reality and augmented reality will yield more adaptable and dynamic applications, while VR will see increased utilization in urban planning and restorative effect studies.

6. CONCLUSION

Due to technical advancements, representations of virtual environments are getting progressively more realistic. The advancement of virtual reality has markedly enhanced our comprehension of urban acoustics and environmental perception. Despite advancements, many study deficiencies exist in this domain. Initially, ecological validity must be enhanced in VR-based soundscape research. Furthermore, additional research is necessary to examine how various demographic groups (the elderly, children, and sensory sensitivities) interpret VR. The rapid development of VR is anticipated to lead to a surge in research within this domain. This study seeks to systematically analyze existing studies and offer guidance for future research endeavors.

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