Measuring the influence of audio on immersive experience in extended reality and digital games: a systematic review

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***Abstract*— A key goal of extended reality (XR) technologies and digital games is to create immersive experiences for the user. Immersive experience is a multifaceted phenomenon that encompasses perceptual and psychological factors, and audio has been recognized as a key modality that can influence such experiences. Despite extensive research on the subject, there is no consensus regarding the ways in which audio impacts immersive experience. This is also the case in terms of the most appropriate methodology for evaluating this phenomenon in the context of end-user experience in XR and digital games. This paper aims to establish a comprehensive overview of the experimental methodologies associated with this topic through a systematic literature review of the last 20 years of research. The inclusion criteria focuses on research papers that attempt to measure audio-related independent variables (e.g., spatial resolution) on immersion-related dependent variables (e.g., sense of presence), in the context of XR environments and digital games. The results reveal a preference for VR HMD and headphone-based experiments, identifying a lack of AR/MR exploration, as well as the necessity for standardized, audio-specific questionnaires in data collection for a more comprehensive understanding of the field.**

***Keywords*— immersion, audio, sound, extended reality, games, immersive, presence, systematic, review**

I. Introduction

Immersion is a phrase that is omnipresent in the fields of extended reality (XR), digital games and audio technology. However, there are still ongoing discussions on how to both accurately define and measure this phenomena [1, 2], and the influence that audio has on it [3, 4]. Aside from the definition of the term being diluted through its overuse as a marketing buzzword to describe a range of new technologies, the confusion also stems from its relationship to other similar terms used in the literature [5]. As [5] explains, the terms 'presence' and 'immersion' are often used interchangeably, but some researchers distinguish them as separate concepts [e.g., 6-9]. A number of researchers consider immersion as a lower-level concept or a determinant of presence [e.g., 7, 10-13], while others regard it as a higher-level concept [e.g., 14-16].

This ambiguity in the definition of the term has led to a lack of consensus across the field of human-computer interaction (HCI), where measuring immersion is an important metric of user experience [1]. Within this field, XR and digital games are perhaps the most common that categorize immersion as a key goal of their content. This is likely due to the fact that these technologies are typically classed within the domain of entertainment, where creating an immersive experience is an important consideration [17]. Both XR and digital game technologies fall under a category of media that can be referred to as interactive virtual environments (IVEs), which differ from 'passive' virtual environments in that they integrate human responses into their reproduction in real time [18]. For example, in terms of audio, this could mean a responsive sound is triggered by a player's action within a digital game environment. In XR, where technology typically incorporates a head mounted display (HMD), head-tracking systems can be used in conjunction with sensorimotor contingencies to enable the IVE to dynamically adjust the spatial representation of audio based on the user's gaze direction [19]. By contrast, a passive virtual environment would simply playback the audio without any variation by human interaction. Since immersive experience is most crucial within IVEs, this study will consider how audio influences immersive experience within these environments through a systematic review.

II. Background

A. Defining Immersive Experience

To resolve the uncertainty in the definition of 'immersion', [5] proposes a conceptual model of immersive experience in XR, seen in Fig. 1. According to this model, immersive experience is the apex construct, resulting from key factors such as physical presence, social/self presence, and involvement. This broad understanding of immersion separates the term into two facets: immersive system/content—representing the technological aspects and similar to the definition of 'system immersion' in [20]—and immersive experience, denoting the psychological experience of immersion [21]. The model also considers the subjective factors that may impact the level of immersive experience on an individual basis. This theoretical structure provides the framework for the present study and will be elaborated in subsequent sections.

Of the numerous concepts encapsulated in the model presented in [5], presence and involvement hold significant importance in the design of IVEs. The primary objective in crafting IVEs often centers on fostering a heightened sense of presence. This makes it a crucial measure for understanding user experiences within IVEs across a broad range of applications from entertainment to education and therapy [22-24]. Biocca [25] discerns three dimensions of presence, Which has been further explicated in [26]. These are:

(1) *Physical Presence:* Virtual physical objects are experienced as actual physical objects.
(2) *Social Presence:* Virtual social actors are experienced as actual social actors.
(3) *Self Presence:* The virtual self is experienced as the actual self.

Simultaneously, involvement—a term frequently used interchangeably with cognitive absorption—originates from digital gaming research and contributes heavily to the

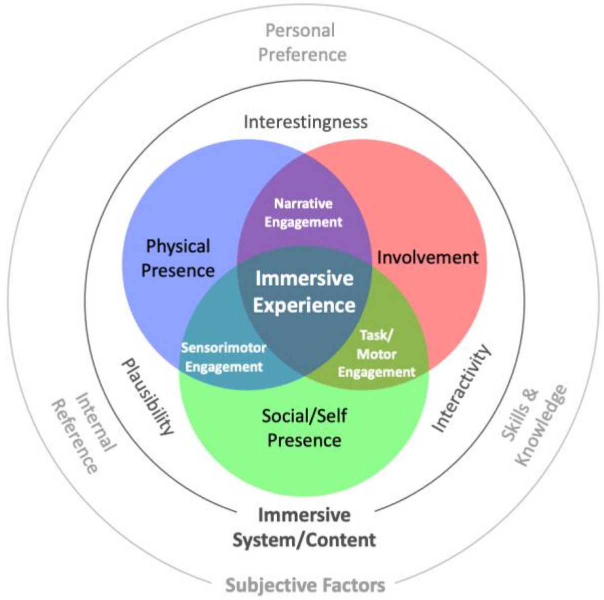

Fig. 1. Lee's [5] conceptual model of immersive experience in extended reality

immersive experience [27, 28]. Calleja [28] constructed a theoretical model for digital game involvement that contends that deep involvement engenders a state of 'incorporation', which echoes the concept of 'immersive experience' in [5]. Another common term mentioned particularly in the digital game space is 'flow' [29]. Both flow and immersive experience share conceptual overlap in terms of involvement and dissociation from the physical world, but while flow is characterized by enjoyment and positively influences mindset, immersive experiences can lead to negative emotions and do not necessarily require tasks with a reasonable chance of completion or a sense of control [5].

B. *Auditory Immersion*

Directing our focus towards how audio impacts immersive experience, as understood by the model in [5], it is important to observe its effect on each key factor separately. A comprehensive examination of audio aspects that impact presence has been examined in [3, 4]. These studies illuminate how auditory stimuli can impact presence—a sense of "being there"—in IVEs through various categories including the spatial properties of sound, the auditory background, consistency within and across modalities, and the quality and contents of sound [3, 4].

The spatial properties of sound, such as room acoustic cues and localisation cues, significantly influence the sense of presence in IVEs, a notion well-documented in the literature [30-33]. Additionally, the auditory background—continuous streams of auditory information—forms an essential part of the immersive experience by closely replicating the richness of real-life auditory landscapes [3, 30, 34]. The role of multisensory congruency is also crucial, as inconsistencies in sensory input can disrupt the sense of presence within multimodal IVEs [35-37]. Lastly, sound quality and contents—ranging from spectral characteristics to the psychological interpretations associated with certain sounds—also play a significant role in shaping the immersive experience [37, 38].

However, presence is only part of the immersive experience as posited by the model presented in [5], with involvement being the other major component. Van Elferen [39] addresses this facet through the development of a theoretical model for musical immersion in the context of digital games, detailing three factors in which music contributes to player involvement —affect, literacy, and interaction. Music affect, the emotional connections created by musical elements, enhances player involvement by creating a deeper personal investment in the IVE [40]. Music literacy, players' understanding of game sound design and its intertextual references, also profoundly influences immersion [41]. Lastly, music interaction, a direct connection between player actions and the game soundtrack, forms another crucial link in enhancing player involvement [39]. Despite this detailed model, research into audio's role in digital game involvement, particularly in terms of sonic components, remains sparse.

C. *Measuring Immersive Experience*

The measurement of immersive experiences is closely tied to the study of presence, with methodologies often intersecting. Despite some methods being centered around the 'involvement' factor of immersive experience, they're frequently applied to measure presence [8]. The approaches to measuring presence are highlighted in a systematic literature review in [2], which showed that 96.6% of 239 virtual reality studies used questionnaires to measure presence. Among the questionnaires, the Slater-Usoh-Steed questionnaire (SUS) [42] and the Presence Questionnaire (PQ) [13] were most commonly used. However, a significant number of different questionnaires have been formulated due to differing conceptualizations of presence and application contexts. Recent efforts to standardize presence measurement have been made through the development of the Multimodal Presence Scale (MPS) [43], which aligns with the model of presence presented in [26].

Optimal presence measurement would ideally be achieved through objective methods such as physiological or behavioral data recording. These methods provide continuous data collection, enabling a more temporally sensitive understanding of presence that isn't reliant on users' recollection of the experience. Physiological methods such as electroencephalography (EEG), heart rate and skin conductance measurements have been used [e.g., 44-46] with EEG showing particularly promising results [e.g., 47, 48]. Despite these advancements, the reliability of physiological measures has yet to be consistently established [1].

The most commonly used questionnaires sparingly include audio-related questions [e.g., 13]. Attempts have therefore been made within the literature to develop audio-specific measurement tools for immersive experience. These include [33], which developed a questionnaire to assess immersion in virtual acoustic environments, and [49], which attempted to amalgamate aspects of overall listening experience and presence in their 'Overall Immersive Audio Experience' questionnaire. However, these attempts face limitations due to their lack of theoretical grounding, context adaptability, and validity of application within non-passive virtual environments. Wycisk et al. [50] also contributed with the development of the 'Immersive Music Experience Inventory', which presents a robust and valid measure for immersive music experience. Whilst this is an extremely useful addition to methodological approaches for measuring immersion in passive music listening experiences, it also requires further validation on its effectiveness in IVEs and non-music audio environments.

Due to the growing interest in this area of study, there have recently been reviews of similar topics observing the role of audio in user experience specifically across specific domains of Virtual Reality (VR) [17], Augmented Reality (AR) [51, 52], and digital games [53]. These provide extensive information for each of their respective fields of interest and were influential in guiding the current study. However, a thorough review that examines the various methods used to measure the impact of audio on immersive experiences in all types of IVEs, particularly across XR and digital games, would enhance our understanding of this research field further and provide a more detailed insight into the subject matter.

III. Methods

As the focus of this paper is to provide an overview of the methodological landscape within the literature, the results presented will concentrate on the findings specifically related to experimental methods. The following research questions are proposed to guide the review in relation to research examining the impacts of audio on immersive experience in IVEs:

RQ 1. What are the common experimental designs employed?
RQ 2. What data collection methods are most frequently used?
RQ 3. What are the limitations of these experimental designs and data collection methods?

This study utilizes the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) protocol as the methodological approach to guide the review [54]. This involves a systematic search to identify relevant published research articles. These articles underwent a thorough screening process, involving the assessment of their titles and abstracts. From the selected articles, a subset was chosen for full-text evaluation. Finally, the findings from the reviewed research were synthesized and organized in response to the research questions of the current study.

A. Search Strategy

A comprehensive search strategy was developed to capture the diverse literature on this topic. The search string encapsulated the three core components under study - audio, immersive experiences, and IVEs, including XR and games. The databases targeted were ACM, IEEE, Scopus, as well as the Frontiers in Signal Processing Journal. These were chosen for their relevance to the topics of interest as well as their inclusion in similar reviews [17, 51, 52]. The search strings retrieved matches from the title & abstract, and the searches were conducted on 8 April 2023. The exact search string was as follows:

("Audio" OR "Auditory" OR "Sound" OR "Music") AND

("Immersion" OR "Immersive" OR "Presence" OR "Involvement") AND

("Extended Reality" OR "Virtual Reality" OR "Augmented Reality" OR "Mixed Reality" OR "Virtual Environment" OR "Games")

For ACM and IEEE, the operators for "Title" and "Abstract" were added where appropriate to accommodate for the differences in search methods from between databases

B. Review Procedure

Papers were included or excluded based on several selection criteria, corresponding to the 'reports excluded' reasons given in Fig. 2. The paper must be: (1) published in a peer-reviewed venue, (2) in English, and (3) relevant to the scope of our study - the influence of audio on immersive experience in extended reality. A detailed description of the exclusion criteria applied to the scope of the study is given in Table 1. The search string was used to retrieve all records from the selected databases, with a total of 3517 records identified initially. These citations were exported from the databases and imported into Endnote 20 for screening. Duplicates were removed (n=724), and the titles and abstracts of the remaining 2793 articles were screened based on the aforementioned selection criteria. This led to 2501 exclusions, leaving 292 articles for full-text review. Of these, four were not retrieved, and a further 198 were excluded based on the selection criteria, resulting in 90 studies included in the final analysis. Within these, there were two studies that reported on findings from two separate experiments within the publication, bringing the final number of unique experimental reports included in the analysis to 92. The flow diagram of this procedure is detailed in Fig. 2.

C. Data Extraction and Analysis

Data were extracted from each article based on several key variables. These included the publication type/year, study design, type of IVE medium, type of auditory display used, number of participants, data collection tools, and information on the specific questionnaires/scales used. This approach was aimed at providing a holistic understanding of the research domain and pointing out potential trends or shortcomings in regard to the methodological approach. Variables were gathered, sorted into tables, and critically analyzed for a thorough evaluation.

TABLE I. Details of Exclusion Criteria Used in the Review

Criteria	Details
Audio	To mitigate the risk of attributing findings to other sensory channels inadvertently, any research that did not distinctly isolate the effects of audio was excluded. For instance, in a study analyzing the integration of audio and haptic feedback in a VR environment, it was essential to have separate conditions for both audio and haptic elements. This measure is designed to prevent any misinterpretation of results that could emerge from a multimodal response.
Immersive Experience	Studies not explicitly outlining the relationship of their findings to any facet of immersive experience (defined by the conceptual model in [5]) were omitted from the review. This criteria helps avoid any potential bias in interpreting the results that were not directly attributed to immersion.
IVEs	The review focused on studies of active experiences in IVEs, where users' actions dynamically shape the environment. This includes both digital games and XR environments. However, XR and audio-only environments must include at least dynamic head tracking or responsive sound reproduction to be considered 'active.'

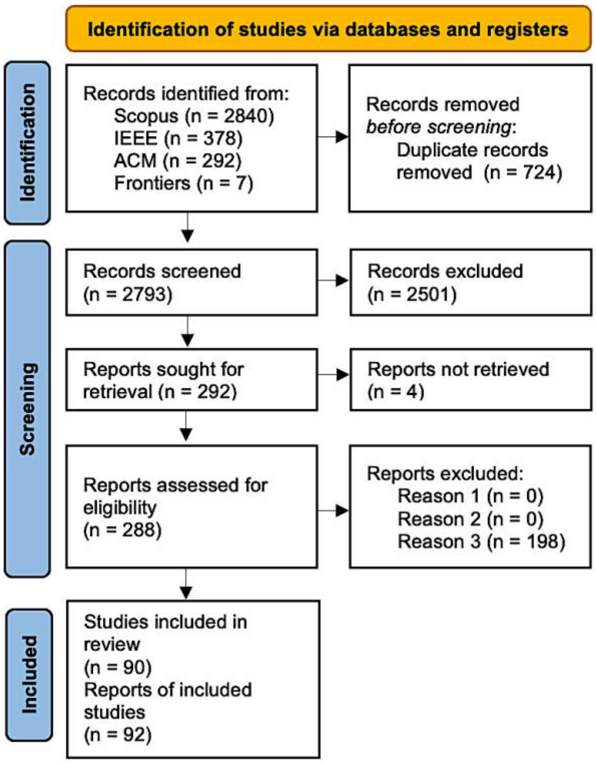

Fig. 2. PRISMA flow diagram for the screening process

IV. Results

A. Publication Details

The details of the publication type and year published can be seen in Fig. 3. The final 90 reports included in the analysis contained 51 conference papers (56.7%), 38 journal articles (42.2 %) and one book chapter (1.1%). The most frequent year for publications was 2019, with 15 studies total. As can be seen, interest in the topic has seen significant growth in recent years. A total of 45 publications (50%) included in the analysis were published earlier than 2019 (2003 - 2018 inclusive). This shows a drastic increase in publications from 2019 - 2023. It should be noted that the low number of publications in 2023 (n=1) is due to the searches being conducted in early 2023.

B. Experimental Setup

In this section, we provide an overview of the experimental setups identified in the review. This includes the media-type used, the number of participants, and the experimental design from 92 individual experiments. It's crucial to note that one study measured immersive experience across two separate conditions, including both a VR with Head Mounted Display (VR HMD) and a screen with keyboard and mouse [55]. This unique approach brought the total count of media-specific studies to 93. The distribution of studies by media type, in relation to the audio reproduction method, is illustrated in Fig. 4.

The media types deployed across the studies spanned the spectrum of XR and screen based digital games. The most prevalent was VR HMD (n=49), followed by screen with keyboard and mouse (n=21), and screen with controller (n=8). Other media types included Mixed Reality (MR) HMD, MR Audio only, and Touchscreen, each appearing in three studies, as well as AR HMD, VR CAVE (Cave Automatic Virtual Environment), and MR Screen, each included in two studies.

Audio reproduction methods were another pivotal aspect, as they helped identify which playback methods, headphones or loudspeakers, were more extensively assessed. A single study explored immersive experiences with separate conditions for both headphones and loudspeakers [56], bringing the total number of audio reproduction studies to 93. Headphones were the predominant choice (n=67), with speakers featuring far less (n=12). A total of 14 studies neglected to specify the audio reproduction type. This strong preference for headphones likely stems from their convenience and prevalence in VR HMD-based studies, as headphones are often integrated with HMDs (e.g., Oculus Quest 2, HTC Vive Pro).

Fig. 5 demonstrates the number of participants involved in each study. Participants were categorized into equal ranges from 1-10 through 91-100, with a final category for studies with over 100 participants. The most populated participant range in the analyzed studies was 11-20 (n=24), suggesting a predominance of smaller-scale experiments. This is confirmed by the majority of studies engaging between 11-40 participants (n=63). Overall, the studies displayed a broad participant range, from a maximum of 1527 [57], to a minimum of six [58]. Given these extreme outliers, the

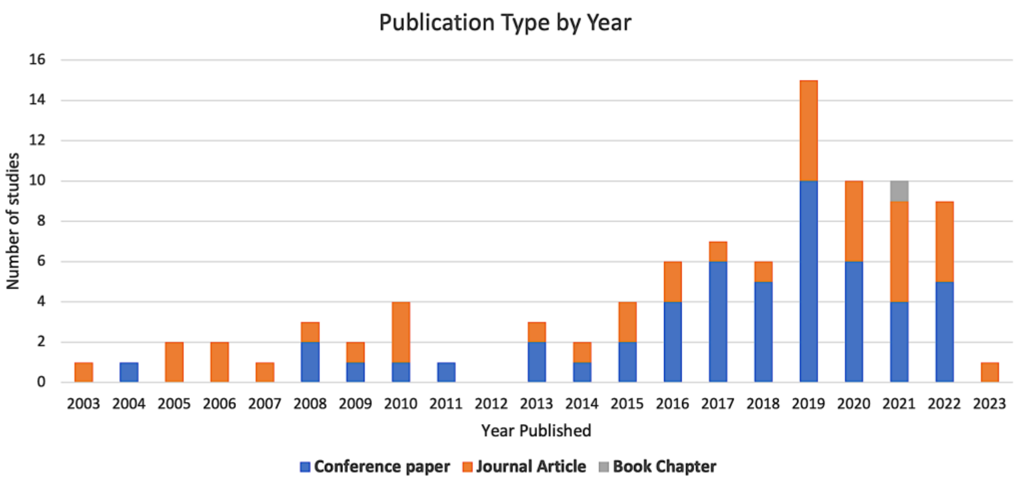

Fig. 3. Distribution of publication by year for reports included in the study

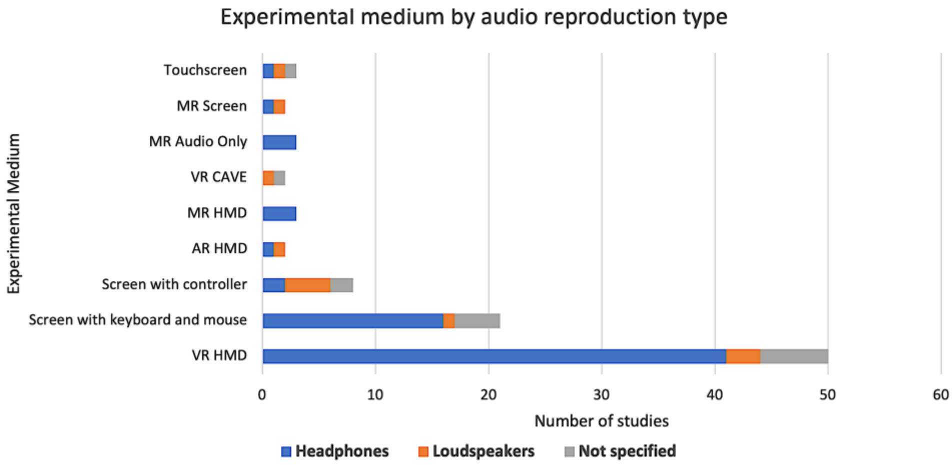

Fig. 4. Distribution of media-type and audio reproduction methods used.

median (*M*=32) participants can be used as a measure of central tendency rather than the mean.

The array of experimental designs used in the 92 studies analyzed is depicted in Fig. 5. There was an almost even split between studies utilizing a between-subjects design (n=42) and within-subjects designs (n=39). The remaining 11 studies adopted a mixed design, frequently seen in factorial experiments, where certain variables were evaluated between groups and others measured within groups.

C. Data Collection Tools

The analysis revealed a range of methodological approaches used for data collection to assess immersive experience, incorporating both subjective and objective measurement tools. Subjective measurements included post-experience questionnaires, semi-structured interviews, and possible configuration choices. The objective metrics employed within the studies included physiological measures, performance measures, and behavioral measures. Fig. 6 presents the frequency of each measurement technique in the surveyed studies, and Table 4 displays all studies included in the review with which data collection tools they utilized. Among these methods, questionnaires emerged as the most prevalent, featuring in nearly all the studies (n=91), leaving one study that did not use this data collection tool. In this novel approach, [59] presented research that sought an alternative method to questionnaires, in an effort to assess 'plausibility illusion' as a key aspect of presence. They employed a Markov transition matrix-based experimental methodology inspired by research in [60] to evaluate the plausibility within an IVE across a range of variables.

Following questionnaires, performance measures were the second most frequent data collection tool, used in 28 studies as objective indicators of immersive experience. The most frequently used performance measures were task completion time (n=10) and task accuracy (n=5), with less commonly used metrics including game score and game progression. This strategy often functioned as a secondary measure of immersive experience to validate questionnaire results, for example by comparing improved task performance to increased immersion levels [e.g., 61]. Physiological measures, employed in 16 studies, involved techniques such as skin conductance (n=9), heart rate (n=7), facial electromyography (EMG) (n=4), eye tracking (n=3), and electroencephalography (EEG) (n=1). Similarly to performance measures, these objective metrics supplemented questionnaire findings concerning immersive experience. Researchers evaluated correlations between the variations in the measured data, such as changes in heart rate, with the level of self-reported immersion from questionnaire responses [e.g., 62].

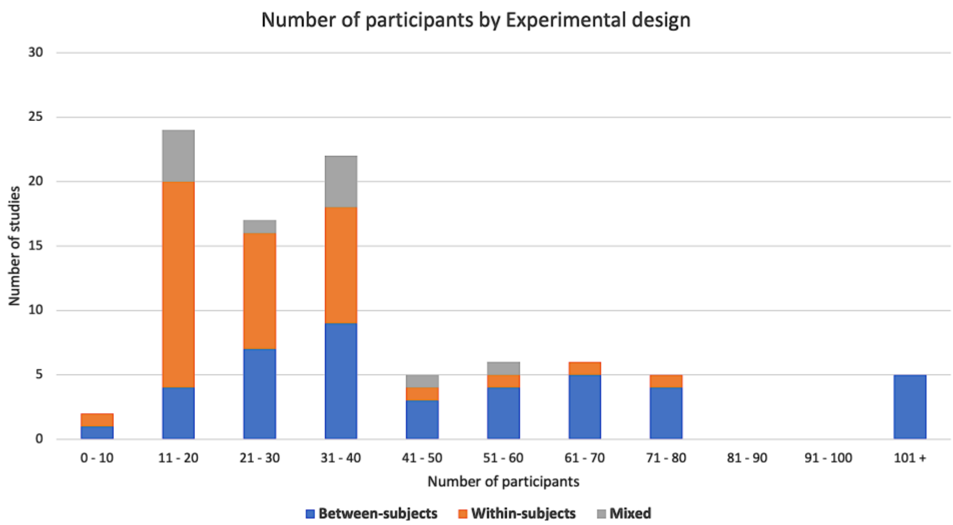

Fig. 5. Distribution of number of participants and experimental design used.

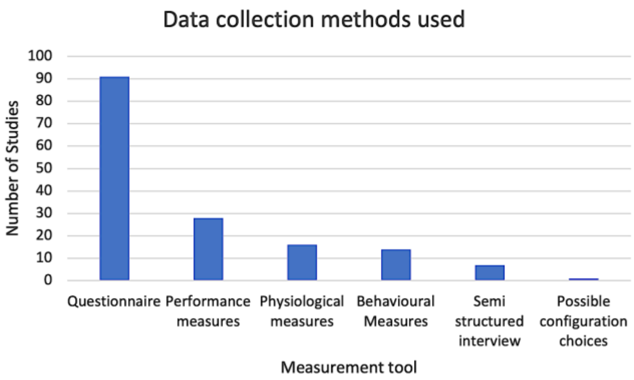

Fig. 6. Distribution of data collection methods used

Behavioral measures were used in 14 studies in order to collect objective data on reactionary responses to stimuli within IVEs. Whilst there were no trends in terms of specific behavioral measures that were commonly applied across the studies, various forms of bodily movement were analyzed. Examples of data recorded as behavioral responses included head height [63], proportion of cautious steps taken [64], and avoidance magnitude [65]. Lastly, semi-structured interviews were administered in seven studies and represented the only purely qualitative measure of immersive experience to be utilized, with the other being open-ended questions that were included in a small number of questionnaires (n=4). These interviews were typically incorporated to provide a deeper understanding of certain aspects of the immersive experience that researchers felt could not be obtained from questionnaires [e.g., 66].

D. Questionnaires and Scales

As seen in the results above, questionnaires emerged as the predominant data collection method across the studies analyzed. Thus, further analysis was undertaken to discern specific patterns in the application of this tool, with the results shown in Table 2. The term 'Bespoke questionnaire' was used in the data collection process to categorize questionnaires that were created by the researchers specifically for the given study. Similarly, 'Amended questionnaire' refers to instances where researchers amended existing questionnaires with their own custom questions.

As indicated in Table 2, Bespoke questionnaires were most frequently utilized (n=29), followed by Amended questionnaires (n=20). Among the pre-existing questionnaires employed, the Presence Questionnaire (PQ) [13] was the most popular, appearing in 14 studies. Subsequently, the Immersive Experience Questionnaire (IEQ) [8], the Igroup Presence Questionnaire (IPQ) [146], and the Slater-Usoh-Steed Questionnaire (SUS) [42] were each featured in ten studies. Out of the remaining 19 questionnaires employed as tools for measuring immersive experience, none appeared in more than five studies. Notably, ten of these questionnaires were only employed in a single study, signaling a significant lack of standardization in methodological approaches for assessing the impact of audio on immersive experiences within IVEs.

In terms of measurement scales, there were two distinct types used to quantify immersive experience, Likert-type scales and sliding scales. The various forms of these scales and their application across the studies can be seen in Table 3. Among the Likert-type scales, 7-point scales were most prevalent (n=45), followed by 5-point scales (n=27). Conversely, sliding scales, featuring 100-point (n=2) and 101-point (n=1) scales, were far less frequently employed. It is worth noting that 13 studies did not specify the exact type of scale used. Given that Likert scales are frequently used to assess attitudes, these results align with conventional research practices [147].

TABLE II. SPECIFIC QUESTIONNAIRES USED

Questionnaire used (source reference)	n
Presence Questionnaire [13]	14
Immersive Experience Questionnaire [8]; Igroup Presence Questionnaire [146]; Slater-Usoh-Steed Questionnaire [42]	10
Game Experience Questionnaire [148]; Player Experience Inventory [149]	5
MEC Spatial Presence Questionnaire [150]; ITC-Sense of Presence Inventory [151]	3
Swedish Viewer-User Presence Questionnaire [152]; Player-Avatar Identification [153]; Social Presence Survey [154]; Game Engagement Questionnaire [155]; Spatial Presence Experience Scale [156]	2
Networked Minds Social Presence Questionnaire [157]; Illusion of Virtual Body Ownership Questionnaire [158]; Immersive Response Questionnaire [159]; Film IEQ [160]; Player Identification Scale [161]; Hendrix & Barfield Questionnaire [30], Draper & Blair Questionnaire [162]; Virtual Body Extension Questionnaire [163]; Temple Presence Inventory [164]; Presence SAM [165]	1
Bespoke Questionnaire	29
Adapted Questionnaire	20

TABLE III. TYPES OF SCALES USED

Scale used	n
7-point Likert type	47
5-point Likert type	25
100-point, 9-point Likert type	2
101-point, 11-point Likert type, 10-point Likert type, 6-point Likert type, 4-point Likert type, 3-point Likert type, Open ended questions	1
Not specified	13

V. DISCUSSION

A. Insights into Experimental Design Trends

In addressing RQ1 (What are the common experimental designs employed?) our observations reveal useful insights into the relationship between the media type and audio reproduction method used. The most utilized media was VR HMD, accounting for over half of the studies. This preference can be linked to VR HMD's inherent ability to occlude real-world stimuli, which is often considered a prerequisite in creating an immersive experience [20]. However, the model in [5] highlights that the exclusion of real world sensory inputs is only a feature of an immersive system, which is a separate concept to immersive experience. This is an important clarification as it dictates which media are considered 'immersive', which is evident in the preference for VR HMD focused studies in the review. This quality is also likely responsible for the predominant use of headphones (found in 72.0% of studies), given that they are often integrated with VR HMDs.

Screen-based digital game media accounted for the second most frequent usage (n=32), a relatively well researched domain given the amount of studies in the review (n=92). Contrastingly, AR and MR are relatively understudied areas

TABLE IV. STUDIES INCLUDED WITHIN THE ANALYSIS AND THE DATA COLLECTION TOOLS USED

Data collection tools	Studies included	n
Questionnaire (Q)	Bialkova & Van Gisbergen (2017) [67]; Bormann (2008) [68]; Brown et al. (2003) [69]; Cáceres (2011) [70]; Chandrasekera et al. (2015) [71]; Chirico & Gaggioli (2019) [72]; Choi et al. (2016) [73]; Dall'Avanzi & Yee-King (2019) [74]; Davies et al. (2017) [75]; Gasselseder (2014) [76]; Geronazzo et al. (2018) [77]; Grassini et al. (2021) [78]; Hong et al. (2019) [56]; Hutchings & McCormack (2020) [79]; Jeon & Jo (2019) [55]; Kariyado et al. (2021) [80]; Kern & Ellermeier (2020)* [81]; Klimmt et al. (2019)* [82]; Lind et al. (2017) [83]; Loureiro et al. (2021) [84]; Lugrin et al. (2016) [85]; Narciso et al. (2019) [86]; Nassani et al. (2022) [87]; O'Hagan et al. (2022) [88]; Oh & Kim (2018) [89]; Outram et al. (2016) [58]; Peck et al. (2009) [90]; Poeschl et al. (2013) [91]; Potter et al. (2022) [92]; Reynaert et al. (2021) [93]; Ryu & Kim (2004) [94]; Sallnäs (2005) [95]; Sanders & Cairns (2010) [96]; Sikstrom et al. (2015) [97]; Sikström et al. (2018) [98]; Sikström et al. (2016) [99]; Skalski & Whitbred (2010) [100]; Vosmeer et al. (2015) [101]; Xu & Kang (2019) [102]	41
Q + Performance	Bhide et al. (2019) [103]; Bremner et al. (2022) [104]; Cooper et al. (2018) [105]; De Oliveira & Tavares (2018) [61]; Hoppe et al. (2019) [63]; Keehl & Melcer (2021) [106]; Lu & Davis (2016) [107]; Ma & Kaber (2006) [108]; Nesbitt & Hoskens (2008) [109]; Rogers et al. (2020) [110]; Rogers et al. (2018) [111]; Viciana-Abad et al. (2014) [112]; Wiemeyer (2013) [113]; Zhou et al. (2007) [114]	14
Q + Physiological	Eloy et al. (2023) [115]; Fröhlich & Wachsmuth (2013) [116]; Geronazzo et al. (2019) [62]; Grimshaw et al. (2008) [117]; Hirway et al. (2020) [118]; Kern et al. (2020) [119]; Lee & Moon (2021) [120]; McArthur (2016) [121]; Nacke et al. (2010) [122]; Ribeiro et al. (2020) [123]; Zhao et al. (2021) [124]	11
Q + Behavioral	Khenak et al. (2019) [125]; Nordahl (2010) [126]; Van Den Hoogen et al. (2009) [127]	3
Q + Semi-structured interview	Gasselseder (2021) [128]; Holm et al. (2020) [66]; Kim & Lee (2022) [129]; McGill et al. (2020) [130]; Smets & van der Spek (2021) [131]; Wagener et al. (2022) [132]; Yang & Sörös (2019) [133]	7
Q + Performance + Physiological	Chan et al. (2017) [134]; Marucci et al. (2021) [135]; Shaw et al. (2017) [136]; Warp et al. (2022) [137]	4
Q + Performance + Behavioral	Durlach et al. (2005) [64]; Kao et al. (2022) [57]; Marto et al. (2020) [138]; Rewkowski et al. (2019) [139]; Rogers et al. (2019) [140]; Sekhavat et al. (2022) [141]; Viaud-Delmon et al. (2006) [142]; Wendt et al. (2019) [143]; Wu & Rank (2015) [144]; Yang et al. (2020) [145]	10
Q + Physiological + Behavioral	Lee et al. (2017) [65]	1
Possible configuration choices	Bergstrom et al. (2017) [59]	1
	Total	92

*Studies that reported on two separate experiments within the same publication

in the literature concerning audio's impact on immersive experience in IVEs. It can be argued that the reasons behind the predominance of VR HMD usage across the studies are inversely contributing to the limited exploration of AR/MR. Given the current understanding of immersion predicates on the suppression of real-world distractions, the nature of AR/MR, which integrates with the real environment, could be seen as less suitable for fostering immersive experiences. However, AR/MR offer important avenues in regards to immersive experiences for audio-visual and audio-only IVEs, as well as having more readily available devices capable of delivering real-time AR experiences as opposed to VR HMD [52]. This highlights a gap in the research, and future work should seek to focus on this relatively underexplored area of immersive experiences.

Regarding the number of participants, the analysis reveals a preference for smaller experiments, as evidenced by the predominant participant range of 11-20 in the reviewed studies. This could be attributed to the complex requirements and preparation necessary for IVE setups. The process of measuring immersive experiences also tends to be time-intensive, with a suggested minimum duration of 10-15 minutes per session due to the limited knowledge of the temporal nature of immersion [6], likely necessitating smaller participant groups. Turning to the experimental designs used, an almost equal split between within-subjects and between-subjects designs was observed. This parity suggests that researchers in the field are balancing the distinct advantages and drawbacks of each design in studying immersion. Within-subjects designs are beneficial in controlling individual differences but can lead to potential familiarity with repeated stimuli, thus affecting immersion levels [6]. On the other hand, between-subjects designs prevent such familiarity effects but may be more susceptible to subjective factors that could influence reported immersion [6]. Careful consideration and reasoning should be applied to future studies when considering the impacts of these experimental designs towards the results.

B. *Types of Data Collection Tools Used*

Addressing RQ2 (What data collection methods are most frequently used?) a diverse range of both subjective and objective data collection methods were used in studies examining the influence of audio on immersive experiences. Despite this variety, post-experience questionnaires emerged as the predominant tool employed in a considerable majority of cases. This prevalence likely stems from their convenience and established utility in capturing subjective experiences [1]. Nevertheless, this approach does present potential drawbacks. The dominance of questionnaires underscore the lack of objective measurement techniques in the field, which offer the potential to measure immersion continuously throughout the experience. This is beneficial as it reduces the potential for recall bias that occurs in post-experience questionnaires. Although this seems ideal, a difficulty in reliability occurs when using objective immersion metrics (such as EEG) to measure immersion caused by changes in audio factors within a multimodal IVE. This is due to the fact that there is not yet clear evidence as to which objective metrics are directly related to this phenomena. There has been promising research conducted in passive audio-only environments [e.g., 47, 48], however further validation is needed to prove its application to multimodal IVEs. Although this is a challenging issue to solve, future works should consider the benefit of a valid objective metric in their research approach.

Performance, behavioral, and physiological measures encompassed the range of objective approaches employed as other measurement tools. These were most commonly used to cross validate results from the questionnaires, in an attempt to reduce bias in interpreting purely subjective data. This pragmatic approach to methodologies for measuring auditory presence has been seen in recent research, with [166] presenting a framework for assessing the level of social presence in virtual musical interactions. Interestingly, over half the studies (n=50) utilized a combination of measurement tools. This shows that multiple approaches are commonly seen in the research, and is likely due to a number of reasons. For example, most studies did not solely measure immersive experience, and often measured other dependent variables that are relevant to user experience in IVEs, such as arousal (n=12), cybersickness (n=5), system usability (n=4), and workload (n=3). As these require a range of measurement approaches, objective measurements were often employed to compare with immersive experience questionnaire results in the analysis. Another reason could be due to the fact that there is not a standardized approach for measuring the influence of audio on immersive experience in IVEs, and therefore a range of approaches were undertaken simultaneously to provide additional data to be interpreted. Whilst the vast majority of studies used quantitative means to measure immersion, semi-structured interviews (n=7) offered a qualitative measure, yielding deeper insights that might not be retrieved from questionnaire responses [66]. This mixed methods approach presents a useful way for researchers to obtain important data about the influence of audio on immersive experience that is missed due to the lack of a standardized quantitative measure, and should be considered as a methodological approach in future studies.

C. Questionnaires Used and their Shorcomings

Questionnaires were by far the most commonly used measurement tool, which confers with previous reviews on presence research [1,2]. In response to RQ3 **(**What are the limitations of these experimental designs and data collection methods?), a deeper examination of the use of questionnaires reveals a considerable lack of standardization and a notable absence of audio-specific questions. The most commonly used questionnaires were purpose-made for the given study (bespoke questionnaires), followed by amended versions of existing tools. While this suggests researchers' attempts to tailor measures to their unique study needs, it also highlights a significant shortcoming in the available questionnaire measures specific to assessing audio's impact on immersive experiences. For example, the most used questionnaires were the PQ (n=14), IEQ (n=10), IPQ (n=10), and SUS (n=10). None of these questionnaires were used in more than 14 studies, and a further 10 questionnaires were only utilized once. Furthermore, out of these most frequently used questionnaires, only the PQ contained any audio-specific questions.

The need for an audio specific measurement tool is evident across the literature, as [167] describes, "In order to measure the effect of different audio settings on presence, additional items and measures would need to be added in future experiments". Similarly, [168] explain in their research on auditory presence that "such further work would be facilitated by the development of a quantitative 'listening scale' which would complement qualitative data collection". In terms of scale types used, Likert-type scales were the primary measurement scales identified. The frequent use of 7-point and 5-point Likert-type scales aligns with common research practices, given their effectiveness in assessing attitudes [147]. However, this does not address the potential for a more nuanced understanding of immersive experiences that could be captured with a wider range of scale types.

D. Limitations

Several limitations in the present study warrant discussion. Concerning the review process, the search terms used and databases chosen could have led to some studies not being included that may have still fit into the criteria. However, an initial number of records identified from the search process (n=3517) proved sufficient in relation to the scope of the research, and so the search terms and databases chosen were justified by the authors. Also, the systematic review focused only on peer-reviewed articles and conference papers published in English, potentially overlooking relevant studies published in other languages or in non-peer-reviewed formats. Another factor that may have induced bias is the single-screening process undertaken by the first author, as a multi-screening process is the recommended approach to reduce potential bias. Due to the scope of the present study, it was decided amongst the authors that this was the appropriate strategy, as it is not a necessary condition for PRISMA reviews [54, 169].

VI. Conclusion

The current systematic literature review has uncovered key trends, methodologies, and experimental designs that mark research investigating the influence of audio on immersive experiences in IVEs. Our analysis indicated a clear preference for VR HMD media and headphones for audio reproduction, attributed to their capacity to occlude real-world stimuli and thus enhance immersion. Despite these findings, the field exhibits a significant gap in the exploration of AR/MR, suggesting the need for future studies in these areas. The review also revealed a predominance of smaller experiments and an almost equal usage of within-subjects and between-subjects designs, evidencing the distinct challenges and opportunities presented by each design in studying immersion. As for data collection tools, a diversity of both subjective and objective methods were observed, with post-experience questionnaires emerging as the most prevalent. The utilization of performance, behavioral, and physiological measures as objective tools and the frequent combination of multiple tools underscored a recognition of the importance of cross validation and the capturing of various facets of user experience in IVEs. Our in-depth exploration of questionnaires, however, highlighted a lack of standardization and an absence of audio-specific questions, signifying a vital area for future development in the field.. In conclusion, while this systematic literature review has shed light on current practices and areas of need in the research on audio's influence on immersive experiences, it has also underscored the richness and complexity of the field, pointing towards numerous avenues for further exploration and development.

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