Research Trends in Virtual Reality Music Concert Technology: A Systematic Literature Review

Jieun Park, Youjin Choi, and Kyung Myun Lee

Abstract—Advances in virtual reality (VR) technology have sparked novel avenues of growth in the musical domain. Following the COVID-19 pandemic, the rise of VR technology has led to growing interest in VR music concerts as an alternative to traditional live concerts. These virtual settings can provide immersion like attending real concerts for physically distant audiences and performers, and also can offer new creative possibilities. VR music concert research is still in its infancy, and advances in technologies such as multimodal devices are rapidly expanding the diversity of research, requiring a unified understanding of the field. To identify trends in VR music concert technology, we conducted a PRISMA-based systematic literature review covering the period from 2018 to 2023. After a thorough screening process, a total of 27 papers were selected for review. The studies were classified and analyzed based on the research topic (audience, performer, concert venue), interaction type (user-environment, user-user), and hardware used (head-mounted display, additional hardware). Furthermore, we categorized the evaluation metrics into user experience, usability, and performance. Our review contributes to advancing the understanding of recent developments in VR music concert technology, shedding light on the diversification and potential of this emerging field.

Index Terms—Virtual Reality, Music Concert, Interaction, Evaluation Metric

1 Introduction

In recent years, as the music industry has transitioned into the streaming era, there's been an amplified desire to attend live concerts with the decline in music sales [10]. Several studies have highlighted that one of the primary motivations for attending live concerts is the unique "environment" they offer compared to mere listening [10, 16]. The specific reasons can vary depending on the genre of the performance: for classical concerts, venue acoustics are a significant attraction for audiences [16], whereas for pop concerts, 'being there' and sharing the experience are primary [10].

Emerging VR technologies have introduced a new dimension of research with virtual concerts gaining momentum in the music sector [48, 63]. The global shift due to the COVID-19 pandemic further boosted technological advancements and interest in virtual concerts. The fusion of VR and music concerts promotes active engagement from both performers and audiences, enriching the musical interaction [63]. Renowned artists are now hosting VR-based performances, and even traditional events like Paris's New Year's Eve celebration have embraced VR for concerts [12]. This trend isn't exclusive to pop; classical genres are also venturing into VR domains [24, 28]. While there is growing interest and technology development in various music genres, the VR music concert field is in its early stages, with a discernible gap in comprehensive understanding and classification of methodologies and assessments. Our study seeks to delve deeper into the intricacies of VR music concerts by addressing specific research questions (RQs):

RQ1: How has the volume of publications related to VR music concerts evolved over the past five years?

RQ2: What are recent trends in VR music concert technology in terms of research topics and interaction types?

RQ3: Which metrics are used to evaluate the performance of technologies and the user experience?

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To answer these questions, we conducted a systematic literature review of selected publications on VR music concerts, following the PRISMA(Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. We focused our review on studies that utilized VR head-mounted displays (HMDs). The selected papers were categorized based on research topic and interaction type, with details provided on the hardware and evaluation metrics employed in these studies. Our analysis offers the latest insights into the realm of VR music concerts and furnishes researchers with a perspective on potential future trajectories.

2 Related Work

While research on VR music concerts is rapidly increasing, there are few literature reviews on the topic. Turchet et al. [63] offer a comprehensive insight into music in extended reality (XR) by detailing how various extended reality (XR) technologies, such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), are employed within the field of music. In this paper, they establish a publication database covering research related to music XR since the 1990s to determine the historical distribution and review a decade of published works (2011 to 2020) to analyze contemporary trends. Specifically, they analyze the historical flow of music research using XR, study types, primary function, target users, social experience (single-user or multi-user), and connectivity (standalone mode or system network).

In contrast to the scope of this review paper, we concentrate on a specific subject, VR music concerts, and provide a detailed categorization of the associated technologies. According to the literature surveyed, there has been a consistent increase in the number of publications related to music XR up to 2020, with a particularly sharp rise in VR-related papers since 2018. Additionally, when examining different sectors within the music industry, it becomes evident that VR usage in the performance sector significantly outpaces its adoption in other areas. Therefore, our review focuses intensively on papers that predominantly investigate VR, specifically those utilizing HMDs, within the context of music concerts. To the best of our knowledge, our paper is the first to identify trends in VR music concert technologies. Importantly, we shed light on the most recent advancements in this field by including papers published after the rise in interest due to COVID-19 (2018 to 2023). We also systematically categorize the evaluation methods of the developed technologies and present which metrics are mainly used. As a result, this review is expected to provide differentiated useful information for researchers by suggesting future directions for VR music concert technologies and metrics. Additionally, the study introduces research

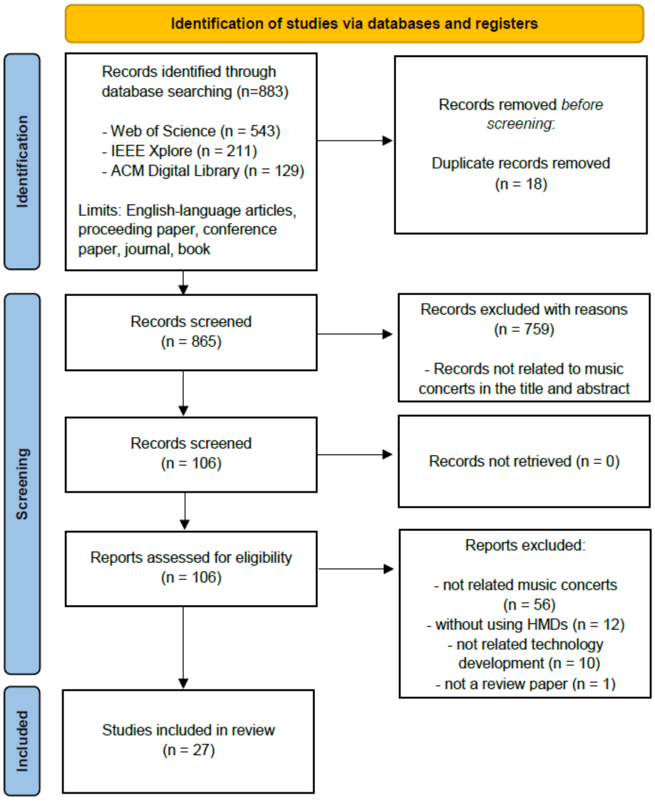

Fig. 1: Implemented PRISMA 2020 process.

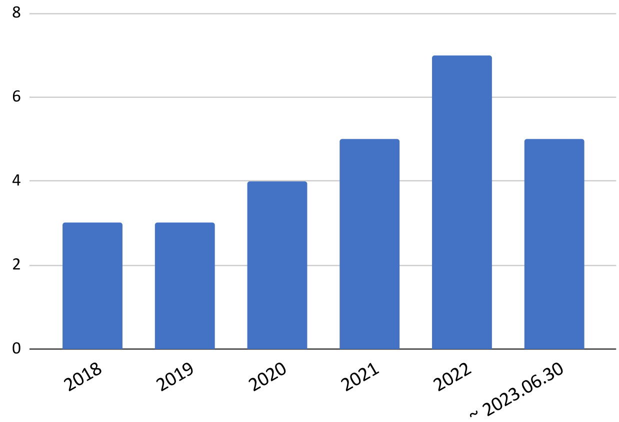

Fig. 2: Publication distribution of VR music concerts over approximately five years.

on the behavior patterns of audiences and performers in real-world settings. This investigation informs the ultimate goal of enhancing the sense of presence and social presence within VR environments. The paper proposes future work that should be conducted in technology development and evaluation to achieve these enhancements.

3 Methods

To review the literature on recent developments in VR music concert technology, we employed a systematic literature review approach based on three stages: identification, screening, and inclusion, following the PRISMA 2020 guidelines [50]. We carried out our research using the Web of Science (WoS) database [14], renowned for its inclusion of high-impact factor journals. And also, we consulted the ACM Digital Library and IEEE Xplore, both of which are comprehensive sources for conferences and journals that showcase the most recent advancements in the relevant field. This approach ensured our search terms were thoroughly represented. The inclusion criteria for analysis were as follows: (1) Literature related to music concerts (excluding movies, theater, drama music, music videos, composition, education, therapy), (2) Using head-mounted display (HMD), (3) Not a review paper, (4) Pertaining to technological developments, (5) The content type corresponds to the following: ACM (articles, proceeding papers) IEEE (conferences, journals, books) (6) Published between January 1, 2018, and June 30, 2023. The publication period was set to approximately the last five years to capture the latest trends in the field. For further details, please refer to Fig. 1.

In the identification phase, we conducted searches to obtain literature related to music concerts by ensuring that the following keywords were present in the abstracts and titles:

("virtual reality" ***OR*** *"virtual environment"* ***OR*** *"VR")* ***AND*** *("concert"* ***OR*** *"audience"* ***OR*** *"performer"* ***OR*** *("performance"* ***AND*** *"music"))*

The following is a detailed explanation of the search terms: The terms "virtual reality," "virtual environment," and "VR" are sometimes used differently by various authors, so we included all three terms in our search. "Concert," "audience," "performer," and "music performance" are terms related to concerts. We included all four words in our search to ensure we captured studies that focused on each individual component. In particular, performance, when used alone, sometimes refers to a technical performance. To avoid this ambiguity, we searched for the term "performance" in conjunction with "music." As a result of the search, a total of 883 articles were identified (as of August 17, 2023). From this, 18 duplicates were removed, leaving 865 articles.

In the screening phase, we reviewed the titles and abstracts of the 865 articles. A total of 759 articles that were not related to music concerts were removed, and an additional 0 articles were excluded due to non-retrieval of records. We then examined the full text of the remaining 106 articles and removed the following: articles not related to music concerts (film, theater, dramatic music, music video, composition, education, therapy, etc.), articles not using HMDs, articles not related to technology development, and review papers. In the inclusion phase, 27 articles were finally included in our review.

4 Results

To determine the overall trend of VR music concert technology, we sorted the documents using specific criteria. We classify and illustrate the papers based on the number of papers published per year, research topic, interaction type, and the hardware used and metrics. Table 1 provides an overview of all the references we reviewed.

4.1 The Number of Publications

According to a paper by Turchet et al. [63], the number of papers covering VR technologies related to music has seen a noticeable rise since 2015. We examined the trend in VR music concert papers from 2018 to June 30, 2023, to understand the current directions in the domain. Fig. 2 displays a noticeable surge in the number of paper publications starting in 2020, coinciding with the onset of COVID-19. This upward trend persists, with a significant volume of papers already published in 2023, despite being just mid-year.

4.2 Research Topic

We categorized the reviewed papers in several ways to identify trends in state-of-the-art VR music concert technology. Initially, we segmented the research topics within VR music concert technology into three categories based on the fundamental components of a concert: Audience, Performer, and Concert Venue. The Audience part includes technologies enhancing the viewers' experience, such as adding visual effects or controlling the NPC audience (48.1%). The Performer segment deals with technologies applicable to performers throughout the entire performance process, from rehearsal to the actual show (37%). Lastly, the Concert Venue category (40.7%) includes studies that examine how

Table 1: Summary of the included publications by research topic, interaction type, HMDs, and additional hardware.

Papers	Research Topic	Interaction Type	HMDs	Additional Hardware
Droste et al. (2018) [24]	Audience / Concert Venue	User - Environment	Oculus Rift	
Horie et al. (2018) [29]	Audience	User - Environment	Not stated	B-Bridge, BrainAthlete / SAMSUNG, Samsung Gear Live
Kaneko et al. (2018) [35]	Audience / Performer	User - Environment / User - User	Oculus Rift	Epson, MOVERIO BT-300 / Microsoft, Kinect
Hajika et al. (2019) [27]	Performer	User - Environment / User - User	LooxidVR	
Ishiyama & Kitahara (2019) [31]	Performer	User - User	Oculus Rift	Microsoft, Kinect
Kasuya et al. (2019) [36]	Audience / Concert Venue	User - Environment / User - User	Samsung HMD Odyssey	Vibration module (no details)
Petrović (2020) [52]	Performer	User - Environment	Not stated	
Petrovic (2020) [51]	Performer	User - Environment	Not stated	
Yakura & Goto (2020) [71]	Audience	None	Oculus Quest 1	
Yan et al. (2020) [73]	Concert Venue	None	HTC Vive	
Beacco et al. (2021) [4]	Audience / Concert Venue	None	Oculus Quest 1	
Chen & Cabrera (2021) [15]	Concert Venue	None	HTC Vive	Sennheiser HD 800 headphone
Lalioti et al. (2021) [39]	Performer / Concert Venue	User - Environment	Oculus Quest 1	
Muñoz-González & Horie (2021) [46]	Audience	User - Environment	Oculus Rift S	B-Bridge, BrainAthlete
Van Kerrebroeck et al. (2021) [66]	Performer	User - User	HTC Vive Pro Eye	Qualisys, OQUS 7+
Abe et al. (2022) [1]	Audience	User - Environment	Not stated	bHaptics, Tactsuit X40 & Tactosy for Arms
Chen et al. (2022) [17]	Concert Venue	None	HTC Vive, Oculus, Varjo	Sennheiser HD 800 headphone
Frank & Perinovic (2022) [26]	Concert Venue	None	HTC Vive	Sennheiser HD380 Pro headphone
Kim et al. (2022) [37]	Audience	User - Environment	Oculus Quest 2	
Muñoz-González et al. (2022) [47]	Audience	User - Environment	Oculus Rift S	B-Bridge, BrainAthlete
Ppali et al. (2022) [53]	Performer / Concert Venue	User - Environment	Oculus Quest 1, Oculus Quest 2	
Wang (2022) [67]	Performer	User - Environment	HTC Vive	Ultraleap, Leap Motion sensor
Chen et al. (2023) [18]	Concert Venue	None	HTC Vive, HTV Vive Pro, Oculus Rift S, Oculus Rift, Oculus Quest 1	Standalone headphones (Sennheiser, Bose, Beats, and AKG)
Jung et al. (2023) [34]	Audience	User - Environment	Oculus Quest 2	bHaptics, Tactsuit X40 & Tactosy for Arms
Meng et al. (2023) [45]	Audience	User - Environment	Not stated	Not stated
Slater et al. (2023) [55]	Audience / Concert Venue	User - Environment	Oculus Quest 1, Oculus Quest 2, Pico NEO	
Son et al. (2023) [57]	Performer	User - User	Not stated	

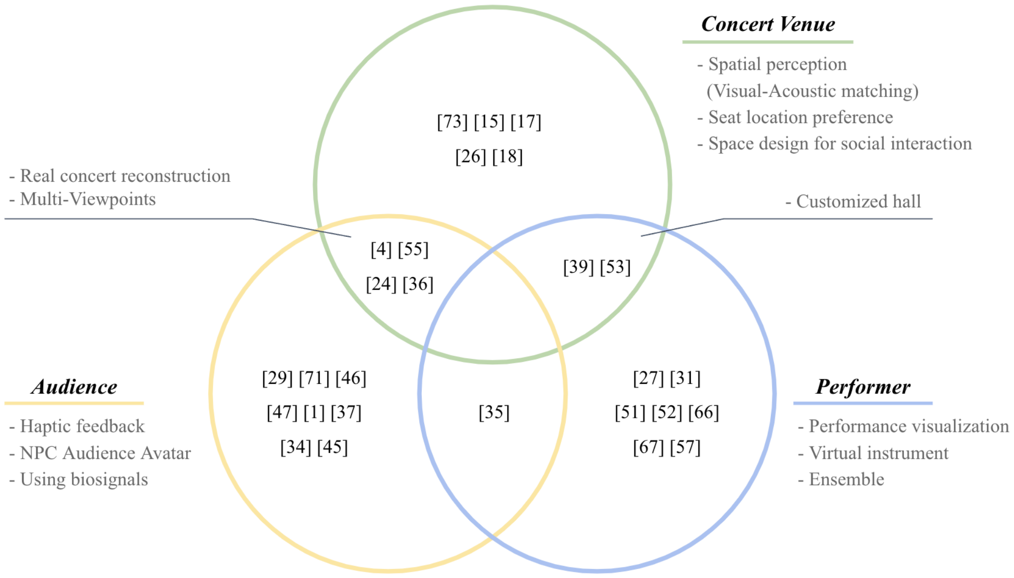

Fig. 3: The Venn diagram of papers categorized by research topic.

users' spatial awareness is impacted by the overall acoustic and visual components of the virtual environment, as well as the creation of spatial designs for specific purposes. Out of 27 papers, 7 (25.9%) address audience or performer topics together. Fig. 3 visualizes the details of the research topic categorization.

4.2.1 Audience

Almost half of all the papers we reviewed, 13 papers (48.1%), are about the audience. 2 papers [4, 55] reconstruct previously recorded performances into a VR setting and evaluate the audience's experience. Recently, during performance recording, cameras, and microphones are variably positioned to enhance the VR experience, such as enabling simultaneous viewing from multiple angles in VR [37]. The audio also adjusts to align with that particular viewpoint, so that the desired sound can be emphasized [24, 36]. Kasuya et al. [36] enhance the sense of presence by introducing vibration that responds to the sound's low frequency from a selected location. Such haptic feedback can be delivered through devices such as controllers or haptic suites, reflecting the performer's movement (e. g., choreography) [34] or audience contact or moshing with NPC audience avatars [1, 35]. Many researchers are intrigued by the presence [4], movement [71], and interaction [1, 35, 55] of NPC audience avatars as they affect the co-presence or sense of unity of the audience. For instance, Abe et al. [1] adjust the behavior of NPC avatars and the concert ambiance based on the audience's heart rate data. Similarly, some research measures the state of the audience during VR music concerts using biosignals like electroencephalogram (EEG) (e. g., bete-alpha ratio) or heart rate. These insights are then employed to generate various visual effects [29, 45–47].

4.2.2 Performer

10 papers (37%) focused on aiding performers in executing performances within VR music concerts. 2 papers [39, 53] present the ability to customize different spaces within VR both visually and acoustically, allowing performers to practice in their desired environment. Another pair of papers [51, 52] address techniques that visualize music created by a performer so that the audience can enjoy the visual representation alongside the music. The development of virtual instruments enables novel performance techniques in VR. Wang's research [67] introduces a virtual piano driven by performance gesture recognition. Son et al. [57] delve into a gesture-based guitar/bass. In this setup, performers, represented as avatars, manipulate instruments using controllers or head movements and can interact with each other. Many papers in our review that target performers specifically focus on ensemble performances. They explored techniques for synchronization between duet performers on various instruments, such as drums, guitars, basses, and pianos in situations where each player appears as an avatar or a real person [27, 31, 57, 66]. Significantly, Hajika et al. [27] measure the EEG synchronization when two players play together, and generate visual effects by using this data to enhance their performance. Besides these interactions between performers, there is also a study on interactions between performers and audiences. In research by Kaneko et al. [35], audiences view performers as avatars via head-mounted displays, and the performers, wearing AR glasses, can immerse themselves in the shared performance experience by observing the audience's reactions.

4.2.3 Concert Venue

A total of 11 papers (40.7%) explore how environmental factors affect user experience in virtual reality (VR) and the development of concert venues specifically designed for VR. In the previous section, we introduced 6 studies that address two kinds of topics together; NPC audience avatar research in VR with reconstructed past actual performances [4, 55], audience perspective manipulation [24, 36], and venue customization [39, 53]. 3 papers explore the relationship between visual or spatial factors, such as the color of the hall [15] and the size and positioning of participants in the room [17, 26], and auditory or acoustic characteristics. And 2 papers [17, 18] analyze seating preferences with respect to the view of the audience. Finally, Yan et al. [73] suggest spatial designs that aim to encourage social interactions between audience members.

4.3 Interaction Type

The evolution of methods for natural interaction within VR settings has emerged as a key discussion point in the current literature [42]. Interaction is such an essential element that it is one of the three characteristics

Research Topic \ Interaction Type	User - User: Audience - Audience	User - User: Audience - Performer	User - User: Performer - Performer	User - Environment: Audience - Environment	User - Environment: Performer - Environment
Visual Effect				[29] [45] [46] [47]	[27] [51] [52]
Personalized Environment / View Point				[24] [36] [37]	[39] [53]
NPC Avatar				[1] [34] [35] [55]	
Virtual Instrument					[67]
Ensemble			[27] [31] [57] [66]		
Social Interaction	[36]	[35]			

Fig. 4: The correlation of research topics and interaction types. The percentage of articles in each category is represented by the brightness of the color.

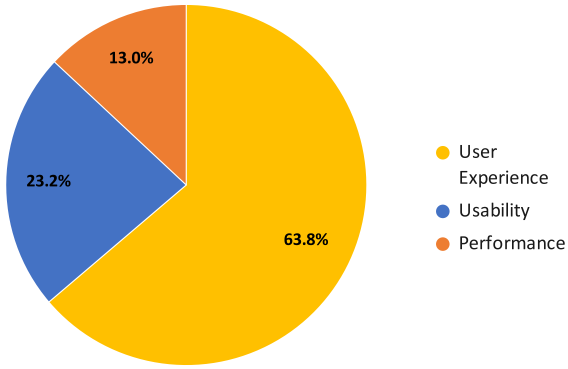

Fig. 5: Distribution of each category of metrics.

of VR presented in the virtual reality triangle. This trend is reflected in our analysis, with 20 out of the 27 papers (74.1%) addressing interactive elements. While previous studies have focused on user-virtual scene interactions, the unique nature of VR music concerts, wherein multiple individuals engage simultaneously, necessitates a classification of these interactions into two types: User-Environment and User-User. Among them, 3 papers integrate both interaction modalities [27, 35, 36]. We also approach the user as either audiences or performers, which allows us to further subdivide the interaction types for more detailed analysis; Audience - Audience, Audience - Performer, Performer - Performer, Audience - Environment, Performer - Environment. Figure 4 shows how interaction types are distributed across research topics in published papers.

Of the 20 papers that include interaction features, the majority, 17 papers (85%), deal with the interaction between the user and the VR environment. Approximately 50% of these technologies use user biometrics or music data to create visual effects [27, 29, 45–47, 51, 52], and another 5 technologies help adjust the environment or viewpoint based on the user's preferences [24, 36, 37, 39, 53]. Other techniques include interaction with NPC avatars [1, 34, 35, 55] and virtual instruments [67]. Within this context, there's a notable push towards multimodal feedback, mostly vibrotactile, as a result of interaction [1, 34, 35]. On the other hand, 6 papers (30%) facilitate interaction between multiple users within a shared virtual space. Over half of them are focused on the performer's ensemble, and there is one paper on each for performer-audience [35] and audience-audience interaction [36]. In the paper by Kaneko et al. [35], it is demonstrated that performers and audiences can enjoy a performance in real-time by observing each other through AR glasses and HMDs, respectively. Kasuya et al. [36] showed that audiences can communicate with one another via Twitter within a VR environment while enjoying the same performance.

As can be seen in Figure 4, the technology developed for user-environment interaction is approximately twice as abundant for audiences compared to performers. In contrast, user-user interaction technology has predominantly been developed for ensembles among performers. A noteworthy trend is the recent increase in research on audience-environment interaction, particularly concerning interactions with NPC avatars. However, research on audience-audience or audience-performer interaction has not been as vigorously pursued.

4.4 Hardware Used

The majority of studies rely on equipment from Meta (previously Oculus) (Oculus Rift, Oculus Rift S, Oculus Quest 1, Oculus Quest 2; 51.9%) or HTC (HTC Vive, HTC Vive Pro, HTC Vive Pro Eye; 25.9%) for implementation and user evaluations. The Samsung HMD Odyssey, Varjo, Pico Neo, and LooxidVR headsets are each referenced once, while some studies did not specify the device model (22.2%).

15 papers used hardware supplementary to the HMD, mostly for collecting biometric data or delivering multimodal feedback. To measure biosignals, 3 studies incorporate additional devices. B-Bridge's BrainAthlete was employed as the EEG device for recording EEG signals, except in one study, which utilized LooxidVR with an integrated EEG sensor in the HMD. Another study employed Samsung's Gear Live to monitor heart rates. 4 studies used Microsoft's Kinect, Qualisys's OQUS 7+, and Ultraleap's Leap Motion Sensor as supplementary instruments for collecting motion data. Tactsuit and Tactosy for arms from bHaptics were chosen to provide vibratory tactile feedback. Due to the theme of their research, which is centered on musical concerts, participants in 5 studies opted to wear headphones instead of using the HMD's built-in speakers.

4.5 Metrics to evaluate the usability of VR concerts

In this section, metrics that previous research employed to evaluate the usability of VR concerts are summarized. These metrics are categorized into User Experience, Usability, and Performance. Of the three types of metrics we categorized, User Experience dominated (63.8%), followed by Usability (23.2%) and Performance (13.0%). Fig. 5 shows the types and distribution of the three metrics.

4.5.1 User Experience

The measurement of *User Experience* is not limited to the measurement of basic usability aspects, but encompasses the comprehensive subjective quality of a user interface experience, including emotional user reactions to the experience [40]. This metric explores the individual and subjective aspects of the user's experience, focusing on the user's attitudes, perceptions, emotions, and psychological responses, in contrast to usability, which measures observable efficacy and efficiency [5]. We categorize them into subjective and objective metrics. Subjective metrics refer to measures of user experience obtained through questionnaires or interviews, while objective metrics utilize biosignals to determine user state. Within the user experience metrics, subjective metrics account for 81.8%, while objective metrics account for 18.2%. Among the sub-metrics of user experience, Presence constitutes the largest share at 22.7%, followed by Emotion (13.6%), Preference (13.6%), Engagement (6.8%), Flow/Immersion (4.5%), and others (20.5%). Notably, all sub-metrics except Biometrics fall under the category of subjective metrics. Figure 6 illustrates the distribution of each category of user experience metrics.

A. Presence

The majority of the papers we reviewed identify *presence* as a user experience metric. For example, [66] uses *Witmer's presence questionnaire scale* [68] to measure presence. Witmer & Singer [69] define presence as "the subjective experience of being in some environment even

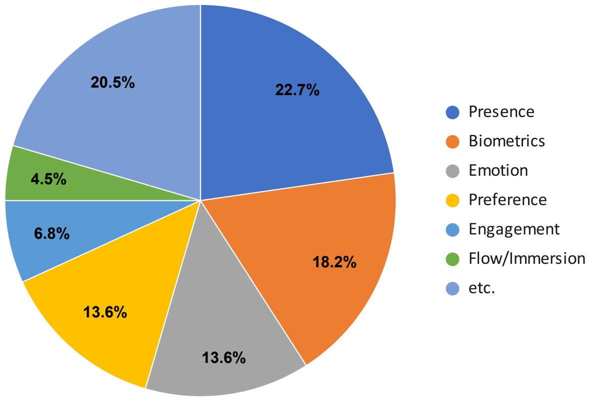

Fig. 6: Instances of user experience metrics.

when physically in another environment". The presence questionnaire scale devised by Witmer et al. [68] consists of 4 factors (Involvement, Sensory Fidelity, Adaptation / Immersion, Interface Quality) and 29 items.

2 papers [45,71] employ the *Slater-Usoh-Steed (SUS) scale*, a widely recognized presence measurement scale in VR environments [54]. Slater's conceptualization of presence encompasses three dimensions: the sensation of 'being there,' an individual's response to this sensation, and the memory of the virtual environment as a real or tangible place [56]. The SUS includes a set of questions related to these three aspects: 'the feeling of presence within the virtual environment (VE),' 'the extent to which the VE becomes the dominant reality,' and 'the degree to which the VE is remembered as a place.' It comprises six items and generates a presence score on a 7-point scale [65]. Additionally, there are studies that validate the presence experience without utilizing a traditional questionnaire [55].

Co-presence is defined by two dimensions: feeling the presence of other individuals in the same space, or feeling part of a group with others [11]. The papers we reviewed also refer to a sense of unity to convey a similar meaning. In this review, a total of 5 papers identify co-presence. 2 papers [1,71] use a modified four-item version of Hwang & Lim's scale [30] to assess co-presence or sense of unity on a 7-point Likert scale. The scale was originally designed to investigate the co-presence of audiences at sporting events, but [1,71] adapt it for the live concert context. In [35,47,55], the authors design their own survey with related questions.

B. Biometrics

Biometrics consist of naturally occurring signals in the human body that are used as objective measures of a user's state and emotions [3]. There are four main types of biometrics used in the studies included in our review: Electroencephalogram (EEG), Cardiac Activity, Electrodermal Activity (EDA), and Pupil Response.

The *Electroencephalogram (EEG)* signal serves as a valuable data source for measuring brain activity, employing various analysis methods such as power spectral analysis, which assesses wave power within specific frequency ranges, and the examination of phase synchrony among multiple individuals [58]. In our review, we identify biometrics analysis utilizing two primary methods. Firstly, the beta/alpha ratio, calculated by comparing the beta band (approximately 13-30 Hz) to the alpha band (approximately 8-13 Hz) of an EEG signal, is used to gauge the level of a flow state, often colloquially referred to as 'being in the zone' [47]. Several efforts are made to employ this beta/alpha ratio to assess the degree of flow experienced by an audience and to generate corresponding visual effects, enhancing the overall immersive concert experience [29,46,47]. Furthermore, the research explores the hyper-scanning method to observe EEG synchrony among two or more individuals [27]. Brainwave synchronization, measured through hyper-scanning when multiple individuals share a common experience, leads to the creation of graphical effects based on the duration of this synchronization.

Various physiological data, capable of monitoring autonomic nervous system activity, are employed as biometrics. Metrics such as *Heart Rate Variability (HRV)* [29] and *Blood Volume Pulse (BVP)* [45], which indicate cardiac activity, along with *Electrodermal Activity (EDA)* [45], an electrical characteristic of the skin that varies with sweat secretion [13], are utilized for assessing physiological arousal. Some studies have harnessed these metrics to create visual effects, as seen in the previously mentioned papers.

Furthermore, *Pupil Response* has been proven effective in estimating the intensity of mental activity, changes in mental state, as well as shifts in attention and alertness [38]. Recent technological advancements have enabled the integration of eye-tracking capabilities into HMDs for monitoring alterations in mental activity, attention, and arousal [66].

C. Emotion

The user's emotional response to a product or service is a critical aspect of evaluating the user experience. Of the 6 papers [4,29,45,46,55,66] that assess users' *emotions*, only one study uses a conventional questionnaire [45]. An alternative approach involves the use of the *Self-Assessment Manikin (SAM)*, a nonverbal pictorial assessment tool that measures pleasure, arousal, and dominance in an individual's emotional reaction to various stimuli [9]. In [4,55], sentiment analysis is conducted by having participants write essays about their overall impressions. Sentiment analysis, also referred to as opinion mining, is a method for examining people's opinions, feelings, and evaluations about a product, service, etc. [43]. Depending on the specific analysis approach, different lexicons and criteria are applied [55], ultimately deriving emotional values for each word to assess the overall user impression. Papers that do not rely on traditional questionnaires or methods instead ask if the user enjoys the system [29,46], or if their experiences are positive [66].

D. Preference

Preference is literally the user's overall preference for the system. Of the literature used in our study, 6 papers identify the preference, typically by asking participants to indicate their degree of preference on an interval scale [17,18,29,46,47] or by asking them to choose from a 2D slider using the HTC Vive controller within a VR environment [15].

E. Engagement

Engagement is the degree of interest and participation in a given situation. In [55], engagement is judged in a rock concert setting by asking participants how much they danced along with other audience members. In [66], the degree of engagement in a piano duet is assessed by asking participants directly or by listening to a recording.

F. Flow/Immersion

Flow is a subjective state that people report when they are so immersed in something that they forget about everything except time, fatigue, and the activity itself. This is characterized by nine dimensions according to Csikszentmihalyi's definition [20]. Among the many measures of Flow, Jackson & Martin [44] were used by [66]. Jackson & Martin's *Short Flow Scale* consists of a shorter, more focused version of the traditional long flow scale. While the original flow scale consists of nine dimensions with multiple questions per dimension, the Short Flow Scale consists of nine questions with one item per dimension [44]. This questionnaire is rated on a scale of 1 to 7. In addition, there is a paper that assesses *immersion*, a concept similar to flow, using a 7-Likert scale [47].

In addition to the subcomponents of user experience discussed above, various studies confirm overall impressions of the experience. While some studies investigate overall impressions through comments and interviews [4,24,37,39,45,47,57], others employ semi-structured interviews [53,66] with a guided set of questions aimed at addressing research objectives [2].

4.5.2 Usability

Usability is defined as "the efficiency and satisfaction with which a particular user can achieve a particular goal in a particular environment" [49]. The papers we reviewed use different usability metrics depending on the purpose of each study. Therefore, we need a standard to categorize the various usability factors and attempt to do so according to *Metrics for Usability Standards in Computing (MUSiC)* [6].

In MUSiC, user-based usability is divided into three key aspects: user performance, user satisfaction, and cognitive workload. User performance involves evaluating the effectiveness and efficiency of system use, assessing the extent to which specific task goals are achieved and the time taken to achieve them. User satisfaction involves measuring user contentment, including perceived usability, which is the subjective evaluation of usability by the participants [60]. Cognitive workload refers to the mental effort required to perform a task. We attempt to categorize the literature reviewed in our paper according to the MUSiC criteria, resulting in a classification into user performance and user satisfaction (perceived usability), except for cognitive workload.

Papers investigating *user performance* include [37], [26], and [24]. In [37], the efficiency of using the system is verified by the user's task completion time. In [26], the effectiveness of a particular system is validated by evaluating the degree to which the relative sizes of space and hearing are cognitively natural. [24] verify that the study objectives are met by asking users whether they completed the viewpoint switching task within the VR environment.

While the academic and professional communities have developed, validated, and used various *perceived usability* questionnaires over the past two decades [60], none of the studies in our review rely on preexisting questionnaires. Instead, they formulate questions tailored to their specific research topics and objectives. Many of the studies that focus on perceived usability evaluated the quality of the technology used. For example, [24, 36] evaluate the quality of audio/visuals when listening to performances from different viewpoints, and [66] evaluates the quality of a piano duo performance based on various criteria. In paper [34], the investigation focuses on the quality of haptic feedback generation, with questions such as "Can the haptic feedback effects be correlated with the performer's movements, and do these haptic effects match the visual stimuli?" Similarly, papers [29] and [46] evaluate the quality of visual effect generation by comparing whether the visual effects generated by a biosignal representing the user's arousal level matched the actual perceived arousal level.

Other research focuses on evaluating the quality of interactions with other users or objects in virtual reality [36, 66]. Metrics assessing overall satisfaction with the positioning and size of elements within the VR environment are also included [37, 47]. In addition, ease of control within the VR environment is assessed [36, 37]. This evaluation primarily includes questions about the intuitiveness of the experience and the ease of task completion.

4.5.3 Performance

Performance measures the effectiveness of a software system with regard to time constraints and resource allocation [19]. To assess it, reviewed papers employ various metrics. *Time* metrics determine the speed of a software system's operation. For instance, studies measure the speed at which people create AR/VR apps [52] and generate content [51]. *Synchrony* metrics evaluate the synchronization of two unique visual or audio inputs. 2 papers [31,66] in the literature reviewed for this study are relevant to the assessment of performance synchrony. In [66], the study investigates a piano duo's performance by measuring both the synchronicity of audio sound and visual movements between the two players. The study [31], on the other hand, focuses solely on audio synchrony, examining timing differences in a drum and bass ensemble. *Accuracy* metrics measure the extent to which technology recognizes a user's movements. Currently, only one study has confirmed the accuracy of gesture recognition in virtual piano playing [67].

5 Discussion

In this section, we will discuss recent trends in VR music concert technology in terms of research topics, interaction types, and metrics for evaluation based on the results reviewed so far.

5.1 The Volume of Publications

With the launch of the first commercially accessible VR HMD, the Oculus Rift, in 2016, a succession of new devices has been rolled out annually by different companies. The desire to utilize virtual environments as an alternative to mandatory physical distancing during the COVID-19 pandemic, combined with ongoing hardware advancements, has driven the expansion of VR music concert technologies. However, even after the lockdowns due to COVID-19 have been lifted, research on VR music concerts using HMDs has continued to see significant growth. In particular, the number of papers published in the first half of 2023 has already almost caught up with the total publications in 2022. This shows that VR music concerts are not just a temporary replacement for real concerts, but are now becoming a new field of research or a way of enjoying music. This suggests that there should be continued interest and development in this area.

5.2 Recent Trends of Research Topic, Interaction Type and Hardware Used

Research on VR music concerts encompasses a wide range of aspects, primarily focusing on audiences, performers, and venues, without a particular bias toward any specific group. Studies that emphasize audience-related aspects often focus on the use of NPC avatars [1, 4, 35, 55, 71]. In contrast, performer-oriented research tends to implement technologies tailored to ensemble performance [27, 31, 57, 66]. Papers on concert venues have often been studied with either the audience or the performer as the target [4, 24, 36, 39, 53, 55], and others have primarily explored how participants perceive the visual and auditory factors in the virtual environment [15, 17, 26].

A significant focus of many studies is on interaction technologies, particularly those that enhance the connection between users and their virtual environment. There is particular interest in developing technologies that seamlessly integrate real-time data from the audience and performer, gathered through wearable devices, to enhance various aspects of the VR experience, including visual effects [27, 29, 45–47] and NPC audience behavior [1, 35, 55]. In addition, the integration of vibrotactile feedback for interactions is a prominent area of research [1, 34, 35]. An interesting observation is that when differentiating users into audiences and performers within the user - environment interaction category, there is a marked focus on technology development for audiences as compared to performers. Notably, there has been a recent uptick in research dealing with interactions involving NPC avatars [1, 34, 35, 55]. On the other hand, research on user-user interaction has only 6 articles and primarily focused on methods for coordinating ensemble performers [27, 31, 57, 66], and only one paper has explored audience-audience interaction by using Twitter [36].

The ongoing advancement of wearable devices, particularly their capability to capture biosignals (i.e., EEG, heart rate device) [27, 29, 45–47] and provide multimodal feedback (i.e., Tactsuit) [1, 34–36], suggests the potential for even more abundant user experiences in VR music concerts [1]. However, the implementation of such technologies likely depends on the simultaneous advancement of hardware, such as the development of HMDs capable of processing finely detailed information about VR concert venues [71], and the improvement of networks to minimize delay and allow multiple users to connect simultaneously [31].

5.3 Metrics and Evaluation Methods

The metrics used to evaluate the developed VR music concert are classified into three primary categories: user experience, usability, and performance, with a significant emphasis on user experience. It's worth noting that subjective metrics are more commonly employed than objective metrics in the majority of studies. Furthermore, the choice of usability metrics tends to vary depending on the specific objectives of each study. Although there are various questionnaires and classification criteria available for assessing usability [6, 60], none of the studies reviewed in this analysis utilized them. Measurements, including questionnaires, must be verified for validity (how well the measurement measures what it is intended to measure) and reliability (the extent to which the results obtained from the measurement and procedure can be reproduced) [8], so the use of previously developed questionnaires allows for more accurate evaluation. Also, recent research on live music performances introduces innovative methods to evaluate audience engagement through physiological synchronization [21, 59, 62]. This approach, which employs physiological indicators to measure the degree of immersion or engagement in a VR music concert, provides a valuable means of quantifying subjective experiences while allowing for real-time objective assessments [3].

5.4 Future Work Opportunities

1) Evolution of Virtual Avatars

Improving avatars that represent themselves or others is important for immersive VR music concerts. The appearance [4, 35, 66], naturalness of motion [1, 55, 71], and interaction [4, 55] of both the user's avatar and the audience's NPC avatar will have a significant impact on the user's presence and social engagement in the virtual environment. To date, available motion data for avatars has been limited, focusing primarily on small areas such as hand gestures rather than the entire body [71]. But considering the importance of physical interaction, such as whole-body dancing in musical communication [41], it is imperative to produce natural whole-body movements of avatars, with particular emphasis on achieving temporal accuracy of movement to music without perceptible delay. The advancement of avatar realism is thus expected not only to increase user satisfaction with the concert experience but also to influence the level of social interaction with the avatar [66]. Furthermore, in order to refine the interaction experience with avatars, it is essential to study and apply the knowledge gained from audience interaction in traditional concert settings [55]. Adopting this holistic approach will further enrich the immersive and socially engaging aspects of virtual reality music concerts.

2) Optimizing Biosignal Integration

In order to enhance the audience's concert experience, it is critical to thoughtfully incorporate biosignals that reflect meaningful characteristics, such as the audience's emotional responses or communicative cues during the concert. The development of wearable head-mounted display (HMD) technology has fostered a growing trend toward real-time use of quantitative neurophysiological metrics such as EEG or heart rate [27, 29, 45–47]. This allows for more creative and dynamic interaction between the user and the virtual reality (VR) environment. However, the indiscriminate use of biosignals, especially when not directly related to the intended state, can result in feedback that lacks relevance to the context of the performance, reducing the sense of unity [33]. Such feedback has the potential to distract the audience by imposing a cognitive load during information processing. To mitigate this, biosignals should be carefully selected, taking into account the specific audience information that designers wish to capture and convey. This strategic selection will contribute to the development of multimodal feedback that enhances the overall VR concert experience. To achieve this, it is critical to understand and monitor the psychological correlates of each biosignal, especially as cognitive neuroscience continues to provide insights into the relationship between EEG signals and acoustic features or the listener's internal state.

3) Extended User Interaction

Our study results clearly indicate the need for the development of technologies aimed at enhancing the interaction between individuals within the VR concert environment [35, 53, 66]. Given that the primary purpose of attending a music concert is to witness a performer's live act, a key aspect is to foster an empathetic experience through real-time interaction between the audience and the performer [72]. Surprisingly, our results indicate a limited number of papers addressing this crucial aspect, with only one identified [35]. This gap underscores the importance of creating technologies that specifically focus on optimizing the connection between the audience and the performer's live experience. While concert performance is traditionally associated with auditory communication, studies in cognitive psychology emphasize the importance of visual information, such as the performer's movements, in establishing an emotional connection [22]. The development of technologies for accurately conveying facial expressions and movements is therefore crucial, and should be complemented by hardware advancements to reduce delays between visual and auditory inputs.

In addition to performer-audience interaction, the aspect of audience interaction in VR concerts also holds significant importance. Attendees seek social engagement and the shared experience of live music [16]. Recent music cognition studies have shown that collective enjoyment of music is enhanced when visual social cues, such as synchronized movements, are present [23]. Unfortunately, our review identified only one study that addressed this aspect [36]. This finding points to the necessity for future research to concentrate on interaction technologies that enable movement synchronization among multiple users. Establishing a multi-user environment, as opposed to limiting interactions to non-player characters (NPCs), is essential for fostering genuine audience interaction in the virtual realm.

4) Developing Concert Venue with Multimodal Feedback

Surveying various research targets and interaction types, it becomes evident that over half of the technologies under investigation are oriented toward audiences. While research naturally prioritizes technologies with broad audience applicability, taking the VR concert experience to the next level requires a reconsideration of what audiences truly value in a live concert setting. As highlighted in the introduction, one of the primary motivations for attending a concert is the spatial characteristics, including acoustics, of the concert venue [10]. The advancement of new technologies exclusive to VR environments, such as personalized environments, unique viewpoints, and innovative hall designs, is crucial, as evidenced in the reviewed papers [18, 24, 36, 37, 39, 52, 53]. And also recognizing and incorporating features from real concert venues that contribute to a sense of reality is equally important. This can be achieved through consultation with stage performance experts or by leveraging insights from research on spatial perception [17, 73]. Additionally, embracing multimodal experiences, such as vibrotactile sensations generated by performances [34] or interactions with surrounding avatars [1, 36], will expand the experiential dimensions beyond sight and sound. With the increased availability of devices capable of transmitting vibrations, such studies have become more feasible, and a surge in research exploring these immersive avenues is anticipated in the future.

5) Subjective Evaluation Enhancement

A recurring theme in future work involves the imperative need for subjective evaluation of emerging technologies [17, 35, 37, 45–47, 52, 53, 66, 71]. Many projects have hitherto conducted technology-effect verifications with a limited pool of pilot subjects. To address this limitation, it becomes crucial to expand the participant pool, conduct user tests under well-designed experimental conditions, and deploy suitable surveys. Furthermore, a comprehensive statistical analysis of the results is indispensable to validate the effectiveness of the developed technologies.

In the realm of cognitive psychology, endeavors persist to measure the immersion or flow of users through various questionnaires and neurophysiological indicators. Mihaly Csikszentmihalyi's flow theory has been a predominant framework, defining the flow as a holistic mental state emerging when an individual is wholly engaged in an action [20]. This has given rise to widely used questionnaires such as the Flow State Scale [32] and the Flow Short Scale [25]. Moreover, an expanding body of research employs autonomic nervous system activation as an objective neurophysiological indicator of flow, utilizing measures of cardiovascular activity (heart rate, heart rate variability) [7, 61], respiratory activity [61, 70], and electrodermal activity [61]. Recent efforts have extended to using EEG [70] and fMRI [64] to scrutinize brain activity during states of immersion. Leveraging established questionnaires and biometrics from psychology not only ensures accuracy but also enhances the effectiveness of technological evaluations. The integration of these validated tools is anticipated to refine and amplify the precision of future technological assessments.

6) Hardware Development

For the mentioned advancements to become feasible, concurrent progress in hardware development is indispensable for facilitating ideal or desired experiments. In parallel, the creation of devices capable of delivering multimodal feedback, such as tactile suits, will significantly contribute to enhancing users' VR concert experiences. This expansion goes beyond the current limitations confined to sight and hearing, offering a more immersive engagement. Addressing the often overlooked aspect of spatial acoustics in VR space implementations will also considerably elevate the overall sense of presence.

6 Conclusion

Recently, the entertainment industry has witnessed a burgeoning interest in VR music concerts. This paper presents a systematic literature review focusing on research trends in virtual reality music concert technologies. We selected 27 papers from different databases using the PRISMA method. Our main focus is on studies that use HMDs and those that deal with environmental implementation or development of related technologies. The selected studies were categorized and analyzed according to their research topic, interaction type, hardware used, and metrics. The research topics can be broadly divided into audience, performer, and concert venue, with some papers addressing multiple aspects. The majority of these papers focus on interaction technologies, with an emphasis on user-environment interactions, while user-user interactions receive comparatively less attention. Also, more than half of the studies incorporate additional hardware alongside HMDs to provide users with a more innovative and immersive experience. We also classified the metrics used to evaluate the developed technology into three aspects: user experience, usability, and performance. Our results showed that user experience metrics are the most commonly used. Although there are some efforts to employ objective measures such as biometrics, the use of non-standard questionnaires is still remarkably common. We expect that our research findings can pave the way for future studies and drive advances in the creation of more immersive VR music concerts.

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References

[1] M. Abe, T. Akiyoshi, I. Butaslac, Z. Hangyu, and T. Sawabe. Hype live: Biometric-based sensory feedback for improving the sense of unity in vr live performance. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 836–837, March 2022. doi: 10.1109/VRW55335.2022.00269 3, 4, 5, 6, 7, 8

[2] O. A. Adeoye-Olatunde and N. L. Olenik. Research and scholarly methods: Semi-structured interviews. *JACCP: JOURNAL OF THE AMERICAN COLLEGE OF CLINICAL PHARMACY*, 4(10):1358–1367, 2021. doi: 10.1002/jac5.1441 6

[3] M. Athif, B. L. K. Rathnayake, S. M. D. B. S. Nagahapitiya, S. A. D. A. K. Samarasinghe, P. S. Samaratunga, R. L. Peiris, and A. C. De Silva. Using biosignals for objective measurement of presence in virtual reality environments. In *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, pp. 3035–3039, July 2020. doi: 10.1109/EMBC44109.2020.9176022 6, 8

[4] A. Beacco, R. Oliva, C. Cabreira, J. Gallego, and M. Slater. Disturbance and plausibility in a virtual rock concert: A pilot study. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 538–545, March 2021. doi: 10.1109/VR50410.2021.00078 3, 4, 6, 7, 8

[5] N. Bevan, J. Carter, and S. Harker. Iso 9241-11 revised: What have we learnt about usability since 1998? In *Human-Computer Interaction: Design and Evaluation: 17th International Conference, HCI International 2015, Los Angeles, CA, USA, August 2-7, 2015, Proceedings, Part I 17*, pp. 143–151. Springer, 2015. 5

[6] N. Bevan and M. Macleod. Usability measurement in context. *Behaviour & Information Technology*, 13(1-2):132–145, 1994. doi: 10.1080/01449299408914592 7

[7] Y. Bian, C. Yang, F. Gao, H. Li, S. Zhou, H. Li, X. Sun, and X. Meng. A framework for physiological indicators of flow in vr games: construction and preliminary evaluation. *Personal and Ubiquitous Computing*, 20:821–832, 2016. 8

[8] O. A. Bolarinwa. Principles and methods of validity and reliability testing of questionnaires used in social and health science researches. *Nigerian Postgraduate Medical Journal*, 22(4):195–201, 2015. 8

[9] M. M. Bradley and P. J. Lang. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, 25(1):49–59, 1994. doi: 10.1016/0005-7916(94)90063-9 6

[10] S. C. Brown and D. Knox. Why go to pop concerts? the motivations behind live music attendance. *Musicae Scientiae*, 21(3):233–249, 2017. doi: 10.1177/1029864916650719 1, 8

[11] S. T. Bulu. Place presence, social presence, co-presence, and satisfaction in virtual worlds. *Computers & Education*, 58(1):154–161, 2012. doi: 10.1016/j.compedu.2011.08.024 6

[12] L. Cacciuttolo. Welcome to the other side: How a social vr concert production broke the world's record of audiences across all media. In *ACM SIGGRAPH 2021 Immersive Pavilion*, SIGGRAPH '21. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3450615.3464950 1

[13] D. Caruelle, A. Gustafsson, P. Shams, and L. Lervik-Olsen. The use of electrodermal activity (eda) measurement to understand consumer emotions – a literature review and a call for action. *Journal of Business Research*, 104:146–160, 2019. doi: 10.1016/j.jbusres.2019.06.041 6

[14] A. A. Chadegani, H. Salehi, M. M. Yunus, H. Farhadi, M. Fooladi, M. Farhadi, and N. A. Ebrahim. A comparison between two main academic literature collections: Web of science and scopus databases. *Asian Social Science*, 9(5), apr 2013. doi: 10.5539/ass.v9n5p18 2

[15] Y. Chen and D. Cabrera. The effect of concert hall color on preference and auditory perception. *Applied Acoustics*, 171:107544, 2021. doi: 10.1016/j.apacoust.2020.107544 3, 4, 6, 7

[16] Y. Chen and D. Cabrera. Environmental factors affecting classical music concert experience. *Psychology of Music*, 51(3):782–803, 2023. doi: 10.1177/03057356221110631 1, 8

[17] Y. Chen, D. Cabrera, and D. Alais. Separate effects of auditory and visual room size on auditorium seat preference: a virtual reality study. *Perception*, 51(12):889–903, 2022. PMID: 36112915. doi: 10.1177/03010066221125864 3, 4, 6, 7, 8

[18] Y. Chen, D. Cabrera, and M. Yadav. Finding the seat with the best view: Stage-view preference for orchestra. *SAGE Open*, 13(2):21582440231181585, 2023. PMID: 37038434. doi: 10.1177/21582440231181585 3, 4, 6, 8

[19] V. Cortellessa, A. Di Marco, and P. Inverardi. *What Is Software Performance?*, pp. 1–7. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. doi: 10.1007/978-3-642-13621-4_1 7

[20] M. Csikszentmihalyi, M. Csikszentmihalyi, S. Abuhamdeh, and J. Nakamura. Flow. *Flow and the foundations of positive psychology: The collected works of Mihaly Csikszentmihalyi*, pp. 227–238, 2014. 6, 8

[21] A. Czepiel, L. K. Fink, L. T. Fink, M. Wald-Fuhrmann, M. Tröndle, and J. Merrill. Synchrony in the periphery: inter-subject correlation of physiological responses during live music concerts. *Scientific reports*, 11(1):22457, 2021. 8

[22] S. Dahl and A. Friberg. Visual perception of expressiveness in musicians' body movements. *Music Perception*, 24(5):433–454, 2007. 8

[23] D. Dotov, D. Bosnyak, and L. J. Trainor. Collective music listening: Movement energy is enhanced by groove and visual social cues. *Quarterly Journal of Experimental Psychology*, 74(6):1037–1053, 2021. 8

[24] M. Droste, J. Letellier, and J. Sieck. An interactive classical vr concert featuring multiple views. In *Proceedings of the Second African Conference for Human Computer Interaction: Thriving Communities*, AfriCHI '18. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3283458.3283501 1, 3, 4, 5, 6, 7, 8

[25] S. Engeser and F. Rheinberg. Flow, performance and moderators of challenge-skill balance. *Motivation and emotion*, 32:158–172, 2008. 8

[26] M. Frank and D. Perinovic. Matching auditory and visual room size, distance, and source orientation in virtual reality. In *Proceedings of the 17th International Audio Mostly Conference*, AM '22, p. 80–83. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3561212

.3561216 3, 4, 7

[27] R. Hajika, K. Gupta, P. Sasikumar, and Y. S. Pai. Hyperdrum: Interactive synchronous drumming in virtual reality using everyday objects. In *SIGGRAPH Asia 2019 XR*, SA '19, p. 15–16. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3355355.3361894 3, 4, 5, 6, 7, 8

[28] R. Hamilton. Collaborative and competitive futures for virtual reality music and sound. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1510–1512, March 2019. doi: 10.1109/VR.2019.8798166 1

[29] R. Horie, M. Wada, and E. Watanabe. Participation in a virtual reality concert via brainwave and heartbeat. In *Advances in Affective and Pleasurable Design: Proceedings of the AHFE 2017 International Conference on Affective and Pleasurable Design, July 17–21, 2017, The Westin Bonaventure Hotel, Los Angeles, California, USA 8*, pp. 276–284. Springer, 2018. 3, 4, 5, 6, 7, 8

[30] Y. Hwang and J. S. Lim. The impact of engagement motives for social tv on social presence and sports channel commitment. *Telematics and Informatics*, 32(4):755–765, 2015. doi: 10.1016/j.tele.2015.03.006 6

[31] T. Ishiyama and T. Kitahara. A prototype of virtual drum performance system with a head-mounted display. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 990–991, March 2019. doi: 10.1109/VR.2019.8797883 3, 4, 7

[32] S. A. Jackson and H. W. Marsh. Development and validation of a scale to measure optimal experience: The flow state scale. *Journal of sport and exercise psychology*, 18(1):17–35, 1996. 8

[33] K. Jung, S. Kim, S. Oh, and S. H. Yoon. Hapmotion: motion-to-tactile framework with wearable haptic devices for immersive vr performance experience. *Virtual Reality*, 28(1):13, 2024. 8

[34] K. Jung, S. Oh, and S. H. Yoon. Mo2hap: Rendering performer's motion flow to upper-body vibrotactile haptic feedback for vr performance. In *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 579–580, March 2023. doi: 10.1109/VRW58643.2023.00132 3, 4, 5, 7, 8

[35] T. Kaneko, H. Tarumi, K. Kataoka, Y. Kubochi, D. Yamashita, T. Nakai, and R. Yamaguchi. Supporting the sense of unity between remote audiences in vr-based remote live music support system ksa2. In *2018 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, pp. 124–127, Dec 2018. doi: 10.1109/AIVR.2018.00025 3, 4, 5, 6, 7, 8

[36] T. Kasuya, M. Tsukada, Y. Komohara, S. Takasaka, T. Mizuno, Y. Nomura, Y. Ueda, and H. Esaki. Livration: Remote vr live platform with interactive 3d audio-visual service. In *2019 IEEE Games, Entertainment, Media Conference (GEM)*, pp. 1–7, June 2019. doi: 10.1109/GEM.2019.8811549 3, 4, 5, 7, 8

[37] M. Kim, Y. Lee, and J. Lee. Multi-view layout design for vr concert experience. In *Proceedings of the 30th ACM International Conference on Multimedia*, MM '22, p. 818–826. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3503161.3548347 3, 4, 5, 6, 7, 8

[38] B. Laeng, S. Sirois, and G. Gredebäck. Pupillometry: A window to the preconscious? *Perspectives on Psychological Science*, 7(1):18–27, 2012. PMID: 26168419. doi: 10.1177/1745691611427305 6

[39] V. Lalioti, S. Ppali, A. J. Thomas, R. Hrafnkelsson, M. Grierson, C. S. Ang, B. S. Wohl, and A. Covaci. Vr rehearse & perform - a platform for rehearsing in virtual reality. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*, VRST '21. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3489849.3489896 3, 4, 5, 6, 7, 8

[40] J. J. LaViola Jr, E. Kruijff, R. P. McMahan, D. Bowman, and I. P. Poupyrev. *3D user interfaces: theory and practice*. Addison-Wesley Professional, 2017. 5

[41] M. Leman. Music, gesture, and the formation of embodied meaning. In *Musical gestures*, pp. 138–165. Routledge, 2010. 8

[42] Y. Li, J. Huang, F. Tian, H.-A. Wang, and G.-Z. Dai. Gesture interaction in virtual reality. *Virtual Reality & Intelligent Hardware*, 1(1):84–112, 2019. doi: 10.3724/SP.J.2096-5796.2018.0006 4

[43] B. Liu. *Sentiment analysis and opinion mining*. Springer Nature, 2022. 6

[44] A. J. Martin and S. A. Jackson. Brief approaches to assessing task absorption and enhanced subjective experience: Examining 'short'and 'core'flow in diverse performance domains. *Motivation and Emotion*, 32:141–157, 2008. 6

[45] X. Meng, Y. He, and K. Kunze. Towards enhancing a recorded concert experience in virtual reality by visualizing the physiological data of the audience. In *Proceedings of the Augmented Humans International Conference 2023*, AHs '23, p. 330–333. Association for Computing Machinery, New York, NY, USA, 2023. doi: 10.1145/3582700.3583709 3, 4, 5, 6, 7, 8

[46] Muñoz-González and R. Horie. Threshold adjustment of beta-alpha ratio of eeg signal for generation of visual effects in a vr live concert. In *2021 IEEE 10th Global Conference on Consumer Electronics (GCCE)*, pp. 174–175, Oct 2021. doi: 10.1109/GCCE53005.2021.9621854 3, 4, 5, 6, 7, 8

[47] Muñoz-González, S. Kobayashi, and R. Horie. A multiplayer vr live concert with information exchange through feedback modulated by eeg signals. *IEEE Transactions on Human-Machine Systems*, 52(2):248–255, April 2022. doi: 10.1109/THMS.2021.3134555 3, 4, 5, 6, 7, 8

[48] K. E. Onderdijk, L. Bouckaert, E. Van Dyck, and P.-J. Maes. Concert experiences in virtual reality environments. *Virtual Reality*, pp. 1–14, 2023. 1

[49] I. S. Organization. Iso 9241-11: Ergonomic requirements for office work with visual display terminals (vdts). part 11: Guidance on usability, 1998. 7

[50] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, and D. Moher. The prisma 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery*, 88:105906, 2021. doi: 10.1016/j.ijsu.2021.105906 2

[51] N. Petrovic. Digital consumption as art expression: Ontological approach to vaporwave generation. In *2020 Zooming Innovation in Consumer Technologies Conference (ZINC)*, pp. 118–122, May 2020. doi: 10.1109/ZINC50678.2020.9161792 3, 4, 5, 7

[52] N. Petrović. Augmented and virtual reality web applications for music stage performance. In *2020 55th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, pp. 33–36, Sep. 2020. doi: 10.1109/ICEST49890.2020.9232713 3, 4, 5, 7, 8

[53] S. Ppali, V. Lalioti, B. Branch, C. S. Ang, A. J. Thomas, B. S. Wohl, and A. Covaci. Keep the vrhythm going: A musician-centred study investigating how virtual reality can support creative musical practice. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3491102.3501922 3, 4, 5, 6, 7, 8

[54] V. Schwind, P. Knierim, N. Haas, and N. Henze. Using presence questionnaires in virtual reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300590 6

[55] M. Slater, C. Cabriera, G. Senel, D. Banakou, A. Beacco, R. Oliva, and J. Gallego. The sentiment of a virtual rock concert. *Virtual Reality*, 27(2):651–675, 2023. 3, 4, 5, 6, 7, 8

[56] M. Slater et al. Measuring presence: A response to the witmer and singer presence questionnaire. *Presence: teleoperators and virtual environments*, 8(5):560–565, 1999. 6

[57] S. Son, Y. Yang, J. Lee, and G. J. Kim. Fakeband: Virtual band music performance with balanced interface for individual score/rhythm play and inter-player expression coordination. In *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 657–658, March 2023. doi: 10.1109/VRW58643.2023.00171 3, 4, 6, 7

[58] D. P. Subha, P. K. Joseph, R. Acharya U, and C. M. Lim. Eeg signal analysis: a survey. *Journal of medical systems*, 34:195–212, 2010. 6

[59] D. Swarbrick, D. Bosnyak, S. R. Livingstone, J. Bansal, S. Marsh-Rollo, M. H. Woolhouse, and L. J. Trainor. How live music moves us: Head movement differences in audiences to live versus recorded music. *Frontiers in Psychology*, 9, 2019. doi: 10.3389/fpsyg.2018.02682 8

[60] J. L. Tao Yang and D. Bolchini. Deep: Design-oriented evaluation of perceived usability. *International Journal of Human–Computer Interaction*, 28(5):308–346, 2012. doi: 10.1080/10447318.2011.586320 7

[61] Y. Tian, Y. Bian, P. Han, P. Wang, F. Gao, and Y. Chen. Physiological signal analysis for evaluating flow during playing of computer games of varying difficulty. *Frontiers in psychology*, 8:1121, 2017. 8

[62] W. Tschacher, S. Greenwood, H. Egermann, M. Wald-Fuhrmann,

A. Czepiel, M. Tröndle, and D. Meier. Physiological synchrony in audiences of live concerts. *Psychology of aesthetics, creativity, and the arts*, 17(2):152, 2023. 8

[63] L. Turchet, R. Hamilton, and A. Çamci. Music in extended realities. *IEEE Access*, 9:15810–15832, 2021. doi: 10.1109/ACCESS.2021.3052931 1, 2

[64] M. Ulrich, J. Keller, and G. Grön. Neural signatures of experimentally induced flow experiences identified in a typical fmri block design with bold imaging. *Social cognitive and affective neuroscience*, 11(3):496–507, 2016. 8

[65] M. Usoh, E. Catena, S. Arman, and M. Slater. Using presence questionnaires in reality. *Presence*, 9(5):497–503, Oct 2000. doi: 10.1162/105474600566989 6

[66] B. Van Kerrebroeck, G. Caruso, and P.-J. Maes. A methodological framework for assessing social presence in music interactions in virtual reality. *Frontiers in Psychology*, 12, 2021. doi: 10.3389/fpsyg.2021.663725 3, 4, 5, 6, 7, 8

[67] M. Wang. Influence analysis of piano music immersion virtual reality cooperation based on mapping equation. *Applied Mathematics and Nonlinear Sciences*, 8:1499 – 1508, 2022. 3, 4, 5, 7

[68] B. G. Witmer, C. J. Jerome, and M. J. Singer. The Factor Structure of the Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, 14(3):298–312, 06 2005. doi: 10.1162/105474605323384654 5, 6

[69] B. G. Witmer and M. J. Singer. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, 7(3):225–240, 06 1998. doi: 10.1162/105474698565686 5

[70] S. Wolf, E. Brölz, P. M. Keune, B. Wesa, M. Hautzinger, N. Birbaumer, and U. Strehl. Motor skill failure or flow-experience? functional brain asymmetry and brain connectivity in elite and amateur table tennis players. *Biological psychology*, 105:95–105, 2015. 8

[71] H. Yakura and M. Goto. Enhancing participation experience in vr live concerts by improving motions of virtual audience avatars. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 555–565, Nov 2020. doi: 10.1109/ISMAR50242.2020.00083 3, 4, 6, 7, 8

[72] T. Yamamoto and Y. Miyake. Generation of sympathetic space in embodied music communication. In *IEEE SMC'99 Conference Proceedings. 1999 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No. 99CH37028)*, vol. 5, pp. 1045–1048. IEEE, 1999. 8

[73] S. Yan, X. Yan, and X. Shen. Exploring social interactions for live performance in virtual reality. In *SIGGRAPH Asia 2020 Posters*, SA '20. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3415264.3425466 3, 4, 8