Applied Acoustics 221 (2024) 109991

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Influence of virtual audio system on psychological restoration effects of soundscapes: Investigating water sounds of a Chinese classical garden

Xian Shi [1], Zhenyu Guo [1], Yuezhe Zhao [*]

State Key Laboratory of Subtropical Building and Urban Science, School of Architecture, South China University of Technology, No. 381, Wushan Rd, Guangzhou 510641, China

ARTICLE INFO

Keywords:
Soundscape
Psychological restoration effect
Ambisonics
Sound recording
Sound reproduction

ABSTRACT

Various sound recording and reproduction methods were utilized to create virtual replicas of soundscapes and restoration effects of soundscapes were examined in studies. The reproduction quality of different virtual audio systems may impact the restoration effect of soundscapes. However, only a limited number of studies have conducted experiments to explore these influences. In this study, five water sounds from a traditional Chinese garden were recorded and reproduced using the monaural, binaural, and first-order Ambisonics technologies. The study evaluated the psychological restorative effects of both virtual and real-world soundscapes through the perceived restorativeness soundscape scale. Furthermore, the perceived realism and spaciousness of the virtual soundscapes were subjectively compared. The findings confirmed the relationship between fidelity and the restorative effects of virtual soundscapes. Binaural recording and playback using a dummy head and headphones proved to be the most authentic method for recreating restorative sound environments. Ambisonics also yielded relatively consistent rating scores compared to real-world cases, whereas the monaural scheme posed a risk of deteriorating the restoration effect of soundscapes.

1. Introduction

The growing incidence of social stress and emotional problems has drawn attention to the relationship between the natural environment and its potential for psychological restoration. The environments that aid in restoring attention resources or releasing stress are commonly termed “restorative environments”. Two theories of the psychological restoration effect, attention restoration theory (ART) [1] and stress recovery theory (SRT) [2], are widely accepted. The ART posits that limited attention resources play a crucial role in restorative experiences; the SRT asserts that the stress alleviation effect is driven by our initial preference toward specific environments (e.g., the natural environment) [3]. The ART advocates that the recovery environments can be characterized by four dimensions [1]: (a) fascination, where the environment encompasses engrossing elements that need no cognitive effort; (b) being-away, signifying environments should be capable of drawing individuals from their daily stress; (c) compatibility, emphasizing consistency between individuals’ inclination and environment characteristics; (d) and extent, suggesting the environment should be rich enough and coherent to constitute a whole other world.

Recent research shows that not only visual but also auditory elements of the natural environment contribute to a positive restoration effect (see a review of Ratcliffe [4]). Recovery effects of audio-visual soundscape presentations vary significantly from those of visual-only presentations [5]. Hence, the potential importance of soundscape in psychological well-being was emphasized.

Based on ART, Payne developed and evaluated the perceived restorativeness soundscape scale (PRSS) [6], a tool prevalently employed to assess the psychological restoration of specific soundscapes through subjective experiments. Payne and Guastavino (2018) further explored the validation and limitations of the PRSS by examining how participants responded to the questionnaire [7]. Both studies showed the PRSS could differentiate between soundscapes. However, influences of other information, especially visual information, cannot be separated when using the PRSS. While the PRSS was initially developed in English, it has been translated into other languages and used in birdsound soundscape evaluation [8], in park soundscape evaluation [9], and in urban soundscape perception of children (PRSS was revised in this study) [10]. Moreover, recent research adopted PRSS to evaluate sound restoration under virtual audio-visual environments [11,12]. The

* Corresponding author.
E-mail address: arzhyzh@scut.edu.cn (Y. Zhao).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.apacoust.2024.109991
Received 28 November 2023; Received in revised form 29 February 2024; Accepted 21 March 2024

outcomes of these studies also advocate the ability of PRSS to distinguish between different soundscapes. Moreover, the restorative effect of soundscapes has been validated not just through psychological responses but also through physiological indices. For example, Li and Kang compared ten physiological indices and subjective assessments with PRSS by exposing the participants to four typical soundscapes (bird sound, ocean, street, and traffic) [13]. Their study revealed a high correlation between the physiological and subjective results of PRSS.

Although conducting in situ experiments directly [14] is presumed to yield more credible results, numerous studies chose to reproduce soundscapes in the laboratory due to the complexity of experiment design or the limitation of physiological monitoring devices, such as electroencephalograph [13] and electrocardiograms [15].

Both Binaural recording and Ambisonics are frequently employed in soundscape research. ISO 12913-2 recommends binaural recording more strongly since a more standard usage processing and thorough evaluation have been established for binaural technologies [16]. Binaural signals recorded with a dummy head mimic the physical procedure by which the human ear receives sound directly. In other words, it incorporates the interference of the torso and pinnae on acoustics, known as head-related transfer functions (HRTFs). This approach allows for a faithful restoration of soundscapes. Nevertheless, binaural recording devices, such as the dummy head, are neither compact nor cost-effective enough for outdoor soundscape recording. Achieving free dynamic rotation of the head in a virtual sound environment can be challenging, and studies frequently reported poor sound externalization and front-back confusion with earphone-based playback due to the mismatch of HRTFs [17,18]. In comparison, first-order Ambisonics (FOA) combined with multi-loudspeakers array preserve spatial information of soundscapes and allows free head movement under virtual sound environment. However, its spatial resolution is much lower than that of binaural recordings due to the inherent limitations in the order of Ambisonics [19]. Some studies also choose stereo or monaural recording techniques, which are more affordable and feasible, especially for field recording. The stereo recording could also restore limited spatial information when an appropriate loudspeaker system was used. However, when stereo stimuli are transmitted to earphones, the influences of the head-relative transfer functions will be bypassed [20], resulting in inevitable distortions of timbre and spaciousness.

Existing studies have emphasized the significance of high-fidelity virtual reality vision for the psychosocial restoration effect [5]. Moreover, previous studies also found that fidelity could considerably impact specific aspects of soundscape perception. Xu and Kang found that binaural recording substantially influenced the realism, reverberance, and directivity of soundscape compared with monaural recording [21]. The soundscape perception would vary with different acoustic rendering methods even when the same recordings were used [22,23]. Although the evaluated perception dimension in these studies could differ from those in the soundscape restoration effect, it shows that soundscape restoration is also influenced by individuals' prior experience [24], which is in line with soundscape perception. Besides, ART mentions that the restoration environment should connect subjects to a larger world (extent attribution of ART). These features of psychological restoration suggest that the environment should conform to the real-world experience, which stresses the importance of soundscape fidelity.

It is also hypothesized that the methods employed for sound recording and reproduction can also impact the psychological restoration effect of the reproduced soundscape. Although various audio recording and reproduction technologies have been used in restoration-related research [25], the importance of soundscape fidelity has not drawn adequate attention. For instance, some studies either omitted reporting their utilized technologies or mixed stimuli from online databases without specifying the design of virtual audio reproduction.

Among studies of soundscape restoration, stereo recording was a prevalent choice due to the prevalence of dual-channel microphones in modern field recorders. These soundscapes were captured via stereo recording and mixed subsequently. Nonetheless, only a few studies utilized a stereo loudspeaker system to reproduce the stimuli [6,26]; the majority preferred audio playback through earphones [10,20,26,27]. As aforementioned, this method neglects the interference caused by the pinna and torso, resulting in a degradation of fidelity. Binaural reproduction is another widely embraced practice. Certain studies acquired binaural signals through binaural recording [13,28], while others used stimuli from open databases [29]. More recently, a few studies have also adopted multi-channel recording, which enables flexible and fidelity reproduction. In some studies, First Order Ambisonics (FOA) recordings were captured and subsequently downmixed for earphone reproduction [5,30]. Notably, sound studies integrated a head tracking system to facilitate free head rotation during binaural playback, which further enhanced the immersive of reproduction [22,23,30].

Diverse virtual audio technologies have been employed to construct virtual restoration soundscapes. However, only a limited number of studies have assessed the comparability of experimental results obtained from virtual soundscapes with those from in situ tests. The necessity of utilizing complex and high-cost virtual audio systems in psychological restoration investigations remains uncertain, especially considering that many studies have employed relatively simple facilities due to recording challenges in diverse and intricate outdoor environments. Explicit findings regarding perceptual differences between virtual and real-world soundscapes could inform the design of subsequent experiments in the field of soundscape restoration research.

The present study aims to investigate the ecological validity of different virtual audio systems concerning their impact on the psychological restoration effect. The hypothesis is that the psychological restoration of soundscapes will be affected by the fidelity of reproduced stimuli. We conducted a comparative analysis involving three sound recording and reproduction methods: binaural recordings with earphone playback (referred to as binaural in later contents), monaural recordings with earphone playback (referred to as monaural in later contents), and FOA recordings with loudspeaker array playback (referred to as Ambisonics in later contents), in contrast to in situ listening. Both binaural and FOA recording were used as a high-fidelity method in relevant research. For comparison, monaural reproduction is chosen due to its lack of spatial information, particularly the absence of interference from pinnae and torso filters.

This study chose the water sounds of the Chinese classical garden as the potential restorative soundscape and conducted experiments based on water sounds. Water sound, birdsong, and wind were commonly considered potential restorative soundscapes [31,32]. Specifically, water sounds are deemed an essential element of soundscape and are utilized to mitigate noise annoyance as masking stimuli [33,34]. In our preliminary investigation, water sound is one of the major natural sound sources of urban public parks and gardens.

2. Methods

In this work, the psychological restoration of soundscapes was evaluated subjectively using the PRSS under the real and virtual soundscapes. The in situ listening experiment was conducted initially, during which the soundscapes were recorded using various equipment. Finally, the same participants assessed the psychological restoration effect under virtually reproduced soundscapes within a semi-anechoic chamber (3.5 dBA background noise level) of the South China University of Technology.

2.1. Study area and stimuli

Chinese classical gardens contain plenty of soundscape designs, especially water elements like fountains, springs, and waterfalls [35]. Qinghui Garden, one of the four most renowned classical gardens in southern China, served as the study area in the present study. Five typical water sounds within Qinghui Garden (refer to Fig. 1) were

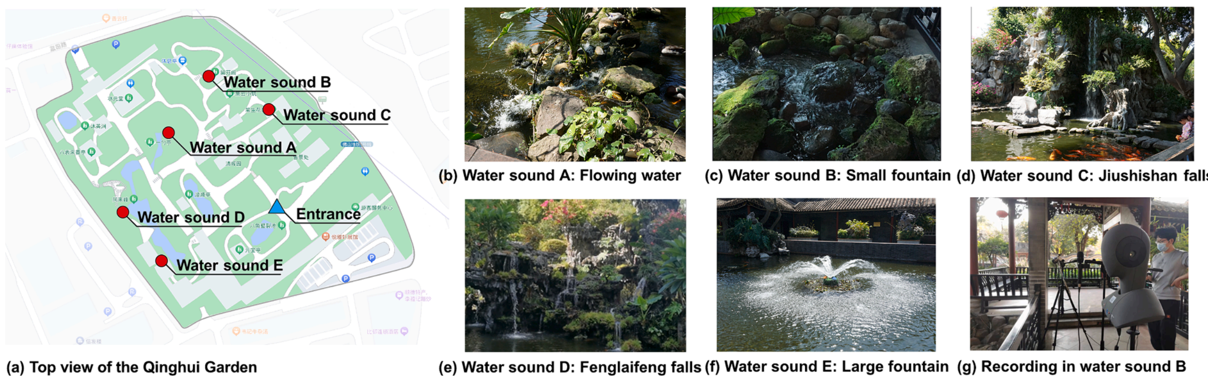

Fig. 1. (a) Top view of the Qinghui Garden, the red dots and blue triangle mark the locations of five water sounds and entrance of the garden. (b)–(f) Five typical water sounds of Qinghui garden. The pictures present the sceneries seen by the participants in the experiment. (g) The picture of soundscape recording in water sound B.

reckoned as a potential restorative soundscape. The first location features flowing water created by two water pools with a minor height variation. The second water sound is a fountain with a low flow rate. The third location, Fenglaifeng waterfall, has a drop of about eight meters, which induces a louder sound. Unlike Fenglaifeng waterfall, Jiushishan waterfall, comprised of multiple small waterfalls situated on an artificial hill, exhibits a relatively smaller drop. The last location features a large fountain with a higher flow rate compared to water sound B.

The sound levels (5-min A-weighted equivalent sound levels) were recorded using a calibrated dummy head (HEAD acoustics HMS III). The detailed recording procedure was introduced in the following Section 2.3.1. The water sound C Fenglaifeng waterfall has the highest sound levels: 72.4 and 73.0 dBA for the left and right ears, respectively. The water sounds D and E also have a relatively high sound level with 68.6 (66.6) dBA and 69.5 (68.7) dBA for the left (right) ear, respectively. As expected, water sounds A and B have lower sound levels, with 66.6 (65.6) dBA and 66.8 (68.3) dBA for the left (right) ear, respectively.

Fig. 2 illustrates the long-time average spectral (LTAS) of five water sounds recorded using a monaural microphone (Brüel & Kjær type 4189). The water sound is relatively stable with time. The deviations between unweighted equivalent levels and levels surpassing 10 % of the time $L_{eq} - L_{10}$ for five water soundscapes were −1.3, −2.0, −0.5, −1.4, and −2.3 dB, respectively. Each spectrum was normalized with its maximum value to achieve a more intuitive comparison. Because water sounds exhibit characteristics resembling random signals, Fig. 2 also

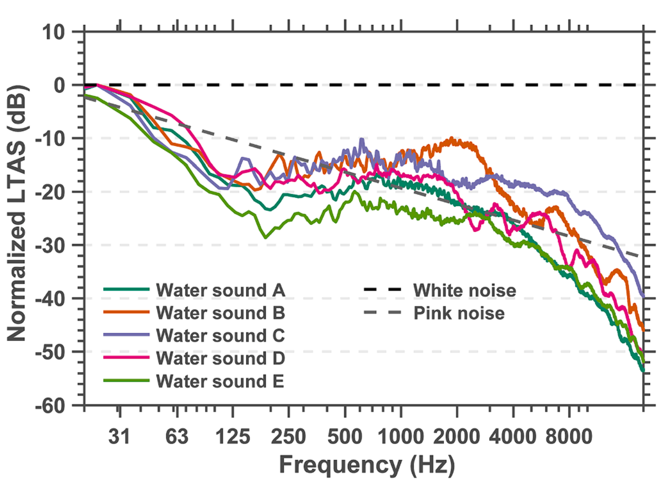

Fig. 2. Normalized long-time average spectral (LTAS) of five typical water sounds. Each LTAS was scaled with its maximum value. The black and gray dashed lines represent the theoretical spectral envelopes of white and pink noise, respectively.

displays the theoretical spectra of white and pink noise. The spectrum envelops of water sound was closer to pink noise. It can be found that the water sound C has higher energy levels in frequencies above 4 kHz. In contrast, another waterfall (water sound D) lacks substantial high-frequency energy like water sound C but displays a noticeable comb filter spectrum structure. It is likely to be formed from the multiple coherent waterfall sound sources, which is a typical structure in the Chinese classical garden. Two fountain water sounds, B and E, have energy concentrations at approximately 2 kHz and 2.5 kHz, respectively. Regarding water sound A, there is a relatively greater distribution of energy in the low-to-middle frequency range below 2 kHz.

2.2. Participants

A total of 22 participants (12 males and 10 females) aged from 23 to 42 years (average age = 26.4, standard deviation = 5.6) were recruited for the in situ listening experiment. All the participants were recruited by advertising on campus and filtered with the criteria of hearing illness history and self-reported recent stress level. No instances of self-reported hearing impairment or medical treatment history were documented. The majority of participants were college students who had recently completed extended periods of study, potentially resulting in elevated stress levels. Fifteen of them were visiting the garden for the first time, and none of the participants had previous exposure to any soundscape or restoration experiments.

In the laboratory experiment, 21 out of the initial 22 participants participated, and 19 of them successfully completed the experiment. The participants were informed of the experimental procedures and granted their informed consent. All participants were remunerated for their time.

2.3. Experimental procedure

2.3.1. In situ experiment

The in situ experiment was implemented on a weekday in March 2022 to alleviate the potential distractions of other tourists. Twenty-two participants were divided into five groups: three groups consisting of four participants each, and the other two groups included five participants each. These five groups of participants sequentially underwent the same experiment procedure. Each group took about one hour to complete the experiment.

The experiment procedure is depicted in Fig. 3(a). Each group of participants received training first, which included an explanation of the concepts of soundscape and restorative effect, as well as an overview of the experimental procedure (there are five soundscapes, and they need to address questionnaires after perception). The meaning of the questionnaire was explained to the participants, and they were instructed to

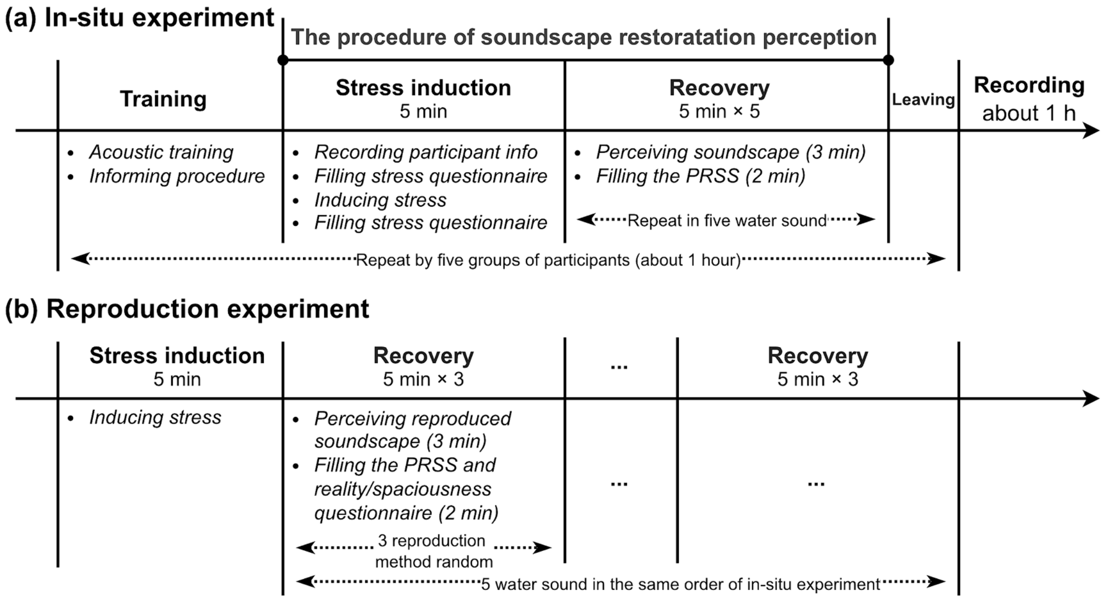

Fig. 3. Procedures of the in situ and reproduction experiment.

focus on the sound environment during the experiment.

Before the formal recovery experiment, the basic personal information and psychological stress level were gathered through a self-reported scale ranging from 0 (high stress) to 4 (high stress). Following this, participants underwent a stress induction phase to ensure a high stress level and attentional fatigue. During this phase, participants sat before the entrance of the Qinghui garden (they could not see the test locations), and they were instructed to imagine a scenario in which they were attending a critical exam. The prompt is "Please imagine the following scene: In the past few months, you have been working hard to prepare for the important examination today. However, in the past week, you have been troubled by many trivial matters and homework, so you feel anxious. Now, the exam is about to start, you find it difficult to concentrate, and you feel stressed" (translated from Chinese). After that, they were required to solve 8 randomly selected puzzles in 5 min [36]. Finally, the stress levels of participants were collected again using the same self-reported scale to evaluate the effectiveness of stress reduction.

During the recovery phase, a guide led participants to each location of soundscape. The guide also recorded the time of perception and instructed the participant to address the PRSS in their personal terminal. Except these, the guide would not disturb the procedure of perception. Participants listened to water sounds for 3 min and filled the PRSS after perception immediately [see Fig. 4(a)]. Each group visited five water sound locations in a randomized sequence balanced with a 5 × 5 Latin square matrix. Note that the relative order was not balanced due to the odd number of groups. The questionnaire comprises four aspects, totaling 14 questions, which assess fascination, being-away, compatibility, and extent. Each aspect consists of three to four questions (see Appendix). A total of 110 (5 water sounds × 22 participants) completed PRSS were obtained in the in situ experiment.

After the entire soundscape restoration perception experiment was finished, the five soundscapes were recorded one by one by three types of systems. In each soundscape location, the recording devices were set up and recorded for about 5 min. Binaural, monaural, and A-format signals were simultaneously recorded using the dummy head and monaural microphone described in Section 2.1 and the FOA microphone (Sennheiser AMBEO VR), respectively. The dummy head and the FOA microphone were horizontally oriented toward the water sound sources. The dummy head had been pre-calibrated, enabling the logging of sound levels for the water sounds. For vision information, a digital camera (Sony α6000) was used to capture video (1080p resolution) simultaneously with the audio recording. All the audio recording devices are directly oriented to the sound source in the horizontal plane. The video recording device was oriented to sound source in both azimuth and elevation [(See Fig. 1 (g)]. Note that there exists a small position disparity among all devices, given all devices were placed at the same height simultaneously. To ensure uniform exposure time to the acoustic environment, all 15 audio and 5 video recordings were cut into 3-min edited files for the subsequent virtual reproduction experiment.

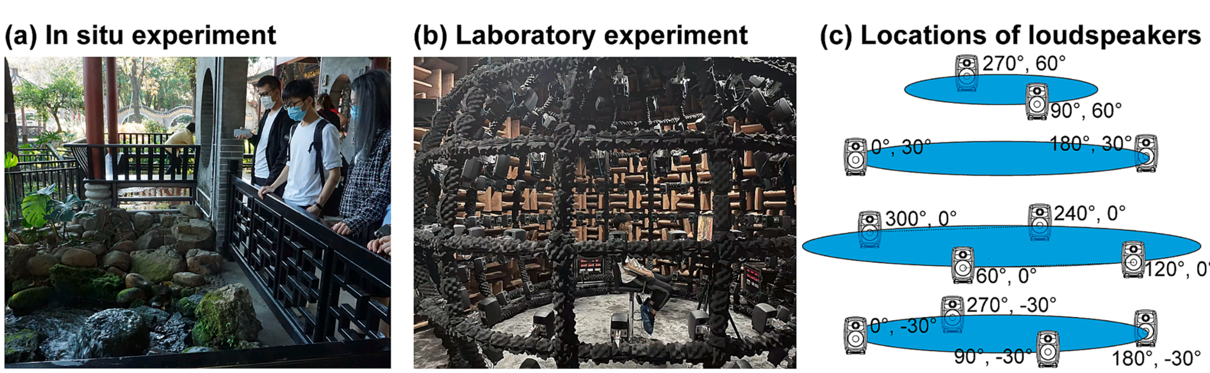

Fig. 4. Photographs of the in situ (a) and laboratory (b) experiments. (c) The spatial distribution of the loudspeakers for Ambisonics reproduction. The coordinate of each loudspeaker position is marked as (θ, φ), where θ and φ denote azimuth and elevation, respectively.

2.3.2. Reproduction experiment

The 3-min edited signals were pre-processed for reproduction first. In the experiment, the videos were presented synchronously with a regular 27-inch monitor positioned in front of the participants. For acoustic stimuli, binaural and monaural signals were played through earphones (Sennheiser HD 500) with dichotic (different stimuli in two ears) and diotic (same stimulus in two ears) mechanisms, respectively. The frequency responses of earphones were equalized with a digital equalizer (HEAD acoustic PEQ V). In terms of Ambisonics reproduction, the outputs of L loudspeakers $\boldsymbol{y} = [y_1, \cdots, y_L]^T$ are the linear combination of four-channel recording signals $\boldsymbol{x} = [x_{FLU}, x_{FRD}, x_{BRD}, x_{BRU}]^T$ from the Ambisonics microphone. The symbols FLU (front-left-up), FRD (front-right-down), BRD (back-right-down), and BRU (back-right-up) indicate the direction of each microphone. The recorded A-format signals were first converted to full 3-D normalization (N3D) [37] Ambisonics signals with a transformation matrix $\mathbf{T}$, as depicted below:

$$\mathbf{T} = \frac{1}{4\sqrt{\pi}}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 3 & 3 & -3 & -3 \\ -3 & 3 & 3 & -3 \\ 3 & -3 & -3 & 3 \end{bmatrix} \quad (1)$$

Subsequently, N3D Ambisonics signals were decoded using the mode-matched decode matrix $\mathbf{D}$ with max-r_E optimization coefficients to minimize the energy spread [38]. Thereinto, the P_N and N denote the nth Legendre polynomial and the order of Ambisonics (in this work $N = 1$), respectively. Twelve loudspeakers (Genelec 8010A, frequency range from 67 to 25 kHz) of the entire array [see Fig. 4(c) for the actual positions] were utilized to reconstruct the sound field. The loudspeakers were positioned in three concentric rings and arranged in a pattern approximating a regular dodecahedron. Only a small part of the entire array was exploited due to evidence suggesting that excessive loudspeakers for a given order could introduce additional spectral distortion [39]. To summarize, the complete Ambisonics signal processing of Ambisonics can be described as follows:

$$\begin{aligned} \boldsymbol{y} &= \mathbf{D}\mathbf{T}\boldsymbol{x} \\ \mathbf{D} &= pinv(\mathbf{Y})diag(a_0, a_1, a_1, a_1) \end{aligned} \quad (2)$$

wherein the *pinv* and *diag* denote the pseudo-inverse calculation and diagonal matrix. The $\mathbf{Y} = [\boldsymbol{y}_1, \boldsymbol{y}_2, \cdots, \boldsymbol{y}_L]$ is composed of all the spherical harmonic up to the first components of the loudspeaker at the spatial position Ω, i.e., $\boldsymbol{y}_L = [Y_0^0(\Omega_L), Y_{-1}^1(\Omega_L), \cdots, Y_1^1(\Omega_L)]^T$.

The sound levels of reproduced binaural stimuli were measured with the dummy head and adjusted to match the levels recorded in the in situ experiment. For monaural reproduction, the average recorded sound levels for both ears were used as the target reproduction levels. For loudspeaker-based Ambisonics reproduction, sound levels were monitored using a dummy head positioned at the array's center and adjusted to match the levels recorded during the in situ experiment. Note that the loudspeaker used in the Ambisonics system has a relatively flat frequency response above around 70 Hz. Hence, the very low frequency contents of the soundscape cannot be presented.

The entire reproduction experiment was conducted during the same weekend as the in situ experiment. Fig. 3(b) depicts the procedure of the experiment, which is similar to the in situ experiment. Before the listening test, participants took stress induction outlined in Section 2.3.1. Stress levels were not assessed via questionnaires on this occasion, as the validity of the stress induction had been determined during the in situ experiment. Next, each participant perceived reproduced water sound soundscapes and answered the PRSS accordingly [refer to Fig. 4 (b)]. Two additional questions for rating reality and spaciousness were attached in the PRSS (see Appendix). Spaciousness emphasizes the sense of direction of the sound, while reality assesses how close the virtual soundscapes are to their actual counterparts. Participants were instructed to rate the score based on these definitions to prevent confusion. For each of the five locations of water sounds, the three types of reproduced methods were perceived and rated in a random sequence. The five water sounds were tested in the same order as the in situ experiment for each participant.

3. Results

The results of these 19 participants who completed both experiments (11 males and 8 females, aged from 23 to 42 years with an average of 26.6 and a standard deviation of 5.7) were included in the primary statistical analysis. The following statistical analyses were conducted with GraphPad Prism 9 if there is no extra explanation.

3.1. Validity of stress induction

Before the formal in situ experiment, participants underwent stress induction to elevate their stress levels above the norm. The validity of the stress induction was verified by comparing the results of two stress value questionaries administered before and after stress induction in the in situ experiment (see Fig. 5). Participants reported their stress levels on a five-level scale ranging from one (large stress) to five (minor stress). Nineteen participants who finished both in situ and laboratory experiments were incorporated in the statistics analysis.

Both reported stress levels before and after the stress induction phase did not conform to a normal distribution according to the Anderson–Darling normality test. Therefore, two sets of scores were compared using the Wilcoxon signed-rank test. The analysis reveals that stress values significantly decreased (indicating a higher stress level) at the 0.05 significance level after participants underwent stress induction ($p = 0.028$). Throughout the subsequent analyses, a result is deemed statistically significant at the level of 0.05.

3.2. Comparison of restoration effects

3.2.1. Overview

The PRSS comprises four dimensions of questions: fascination, being-away, compatibility, and extent. The responses (rated on a seven-level Likert scale, with one representing negative attitudes and seven representing positive attitudes) to multiple questions within each perception dimension were averaged first, inducing a total of 1520 [5 water sound × 4 stimuli types (in situ and three reproduced stimuli) × 4 PRSS dimensions × 19 participants] final ratings.

Four dimensions of PRSS were analyzed separately. The rating scores of each condition conformed to a normal distribution according to the Anderson–Darling test. For each of the four dimensions, a two-way (water sound and stimuli type) repeated-measures analysis of variance (rmANOVA) was performed on the scores. The Geisser–Greenhouse correction was applied to correct the violation of the sphericity assumption. Table. 1 summarizes the statistical results of the rmANOVA, wherein the partial eta-squared η_p^2 represents the effect size. The results

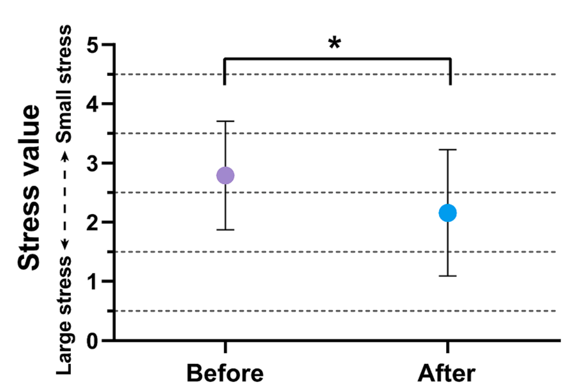

Fig. 5. The recorded stress values before and after the stress induction phase. The asterisk * indicates a significant difference at the level of 0.05.

Table 1
Summary of the rm ANOVA results.

Factor		Fascination	Being-away	Compatibility	Extent
Stimuli type (ST)	F	F(2.06, 37.13) = 9.057	F(1.75, 31.50) = 7.507	F(1.91, 34.36) = 6.612	F(1.80, 32.45) = 9.845
	p	< 0.001***	0.003**	0.004**	<0.001***
	η_p^2	0.275	0.258	0.268	0.321
Water sound (WS)	F	F(2.97, 53.44) = 3.916	F(2.84, 51.10) = 3.397	F(2.65, 47.73) = 5.714	F(2.68, 48.17) = 2.966
	p	0.014*	0.027*	0.003**	0.047*
	η_p^2	0.183	0.187	0.329	0.140
ST × WS	F	F(5.91, 106.30) = 2.307	F(5.78, 104.10) = 2.702	F(5.61, 101.00) = 2.919	F(5.90, 106.20) = 2.565
	p	0.040*	0.019*	0.0133**	0.024*
	η_p^2	0.114	0.131	0.140	0.125

The asterisks *, **, and *** represent a significant level of 0.05, 0.01, and 0.001, respectively.

indicate significant main effects of both stimuli type and water sound on rating scores for all four dimensions. Notably, the stimuli type accounted for a larger effect size than water sound, except for the compatibility dimension. A significant interaction effect between stimuli type and water sound was observed across all four dimensions of restoration.

3.2.2. *Influences of the virtual audio system*

Given the observed interaction effect, a more in-depth examination of simple effects becomes essential. Tukey multiple comparisons were implemented on each water sound. Fig. 6 presents average rating scores of the PRSS across participants under all conditions, and the significant differences between scores of virtual audio systems were marked.

For sound water A, the binaural system yielded results most similar to the in situ results. Monaural system scored significantly lower than binaural system for all four dimensions (p = 0.002, 0.003, 0.008, and 0.003, respectively). However, all three virtual audio systems showed no significant differences between in situ and virtual reproduced stimuli. The scores of loudspeaker-based Ambisonics were lower than binaural system for the compatibility dimension (p = 0.017).

In terms of sound water B, a noticeable disparity between scores of the binaural system and in situ stimuli was identified. It shows that binaural system achieved higher scores compared to in situ stimuli (see Fig. 6), especially for the extent dimension, where the differences were significant (p = 0.031). In contrast, the Ambisonics was nearest to the in situ case. Monaural system got significantly worse scores than binaural system for all dimensions (p = 0.042, 0.007, 0.019, and 0.008, respectively); Ambisonics system also scored significantly lower than binaural system for the compatibility dimension (p = 0.019).

It appears that virtual reproduced stimuli elicited relatively weaker restorative effects compared to the in situ conditions for water sound C. All three types of reproduced stimuli obtained lower scores than in situ stimuli, particularly monaural stimuli, which have significant differences for all dimensions (p = 0.009, 0.020, 0.032, and 0.042, respectively). The monaural stimuli scores were also significantly lower than those of binaural stimuli for the extent dimension (p = 0.049). As for Ambisonics, its scores were lower than its in situ counterparts for the fascination and being-away dimensions (p = 0.024 and 0.034, respectively).

A deterioration of the restoration effect with all the virtual audio system was also observed for another waterfall (water sound D). Monaural system scored significantly lower than in situ for the fascination (p = 0.019), the be-away (p = 0.023), and the extent dimensions (p = 0.003). The Ambisonics encountered significantly worse ratings for the extent dimension than in situ scenes (p = 0.001). Binaural system stimuli outperformed monaural system for the extent dimension (p = 0.027).

In terms of water sound E, the results revealed that the scores of all

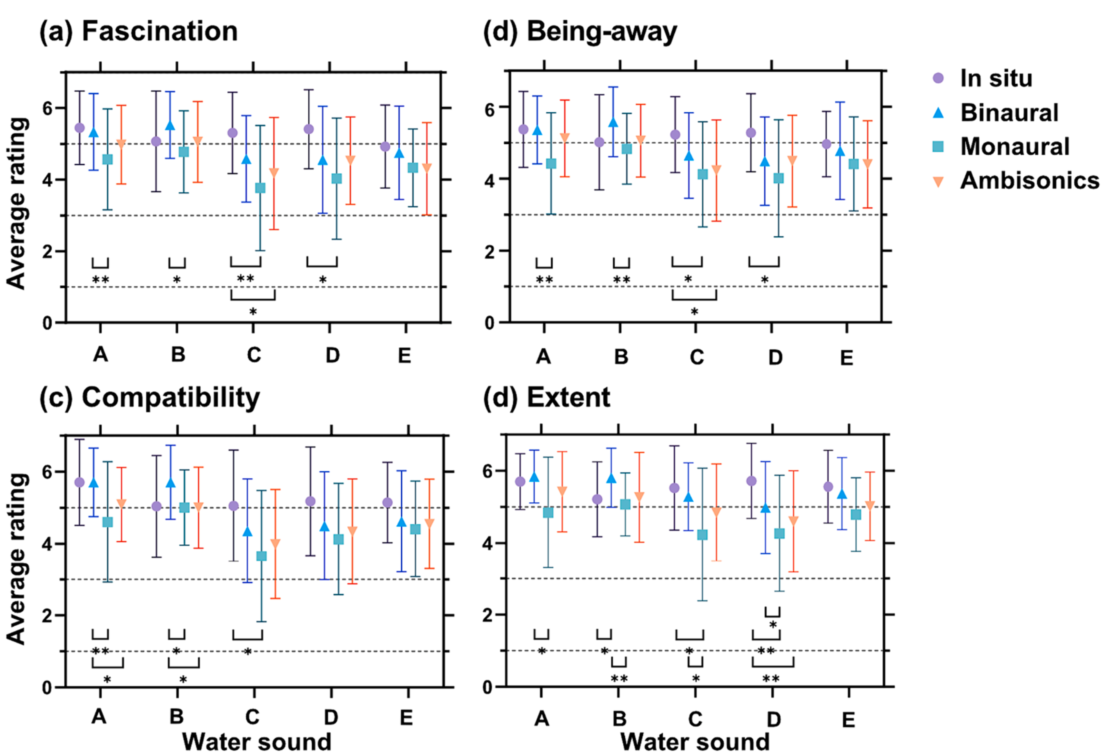

Fig. 6. Average rating scores of the PRSS across participants. The markers represent the scores, and black error bars indicate the standard deviations. The significant differences between virtual audio systems at the level of 0.05 and 0.01 were marked with the * and ** symbols, respectively.

reproduced stimuli closely resembled those of in situ stimuli, especially for binaural system. No significant difference was found compared with the in situ and reproduced stimuli.

3.2.3. Restoration effects of different water sounds

To discern disparities in restoration effects among the five water sounds, we employed identical post-multiple comparisons for each type of stimulus.

Participants gave similar scores for the five water sounds in the in situ experiment. No significant difference was observed among the five water sounds across all dimensions. However, it shows for fascination and being-away restoration, and water sound E has the lowest mean score while water sound A has the highest mean score, with a difference of 0.53 and 0.41, respectively. For compatibility, water sound A obtained the highest scores while scores of other four water sounds were close. For extent, water sound A and D have similar high scores, with a deviation of 0.49 and 0.51 compared to the lowest scores obtained by water sound B.

In the reproduction experiment, things go the other way, where participants show apparent preferences for specific water sounds. For monaural system, the water sound C (Jiushishan waterfall) was rated worse by participants. Significantly lower scores were attributed to water sound C when compared to water sound B in the fascination ($p = 0.034$) dimension and to water sound A Flowing water ($p = 0.034$) and B Small fountain ($p = 0.034$) in the compatibility dimension. Participants tended to give sound water A and B higher ratings for binaural systems. Water sound A achieved significantly higher scores than water sound D (Fenglaifeng waterfall) in the being-away ($p = 0.024$), compatibility ($p = 0.014$), and extent dimension ($p = 0.049$), as well as water sound C ($p = 0.003$) and E Large fountain ($p = 0.041$) in the compatibility dimension. Water sound B received higher recovery ratings compared to water sound C in the fascination ($p = 0.026$), being-away ($p = 0.030$), and compatibility dimensions ($p = 0.006$) and water sound D in the being-away ($p = 0.006$), in the compatibility ($p = 0.026$), and in the extend dimensions ($p = 0.028$). In the case of Ambisonics, water sound C was rated lower than water sound A ($p = 0.017$) and B ($p = 0.430$) for the extent dimension. These findings are in line with the analysis of the preceding section, which demonstrated that virtual reproduction exhibited poorer performance with respect to water sound C.

3.3. Reality and spaciousness of three virtual audio systems

Rating of reality and spaciousness for virtual water sound were gathered separately through two additional questions. The across-participant average scores, along with their corresponding standard deviations, are illustrated in Fig. 7. It clearly shows that monaural system had an inferior quality of reality and spaciousness when compared to binaural and Ambisonics systems. Binaural system achieved the highest rating scores, with Ambisonics scoring closely behind.

The distribution of rating scores did not meet the criteria of the Anderson–Darling normality test. Hence, the one-way Friedman test was conducted for each water sound to compare the three types of virtual audio systems. Monaural system exhibited inferiority to binaural system in water sound A ($p = 0.001$), B ($p = 0.018$), C ($p = 0.045$), and D ($p = 0.045$) for the reality dimension, and water sound A ($p = 0.005$), C ($p = 0.045$), and D ($p = 0.022$) for the spaciousness dimension. Besides, significantly poorer results were observed for monaural system when compared to Ambisonics in water sound C for the spaciousness dimension ($p = 0.022$). In Ambisonics system, no significant differences were observed compared to binaural system.

3.4. Correlation between the restoration effect and the reality/spaciousness

The current study hypothesizes that the fidelity of reproduced sound could influence the restoration effect of soundscapes. Multiple linear regressions were conducted on all five water sounds and three virtual stimuli to investigate potential correlations. Within each regression model, the ratings for the four restoration effect dimensions were dependent on the scores for reality and spaciousness.

The predicted scores via the regression models versus actual scores of participants were plotted in Fig. 8. Four regression models, representing the dimensions of fascination [$F(2, 282) = 91.68$, $p < 0.0001$], being-away [$F(2, 282) = 92.72$, $p < 0.0001$], compatibility [$F(2, 282) = 91.72$, $p < 0.0001$], and extent dimensions [$F(2, 282) = 239.7$, $p < 0.0001$], were found to be statistically significant. Particularly, the regression model for the extent dimension had the highest R-squared value of 0.63, indicating that the extent dimension can be predicted more reliably with the scores of reality and spaciousness.

Comparing the two predictors, reality and spaciousness, it becomes evident that reality exerts a more significant influence on recovery rating scores than spaciousness. The regression coefficients for reality ranged from 0.43 to 0.60 across the four regression models, significantly surpassing the values for spaciousness, which ranged from 0.07 to 0.14. Reality significantly contributed to the dimensions of fascination [$F(1, 282) = 40.98$, $p < 0.0001$], being-away [$F(1, 282) = 47.81$, $p < 0.0001$], compatibility [$F(1, 282) = 43.76$, $p < 0.0001$] and extent [$F(1, 282) = 149.3$, $p < 0.0001$]. On the contrary, spaciousness only exerted a significant influence on fascination [$F(1, 282) = 5.647$, $p = 0.018$] and the compatibility [$F(1, 282) = 4.572$, $p = 0.0334$].

4. Discussion

4.1. Correlations between reality/spaciousness and restoration effects

Generally, the higher the fidelity of the soundscape virtual sound

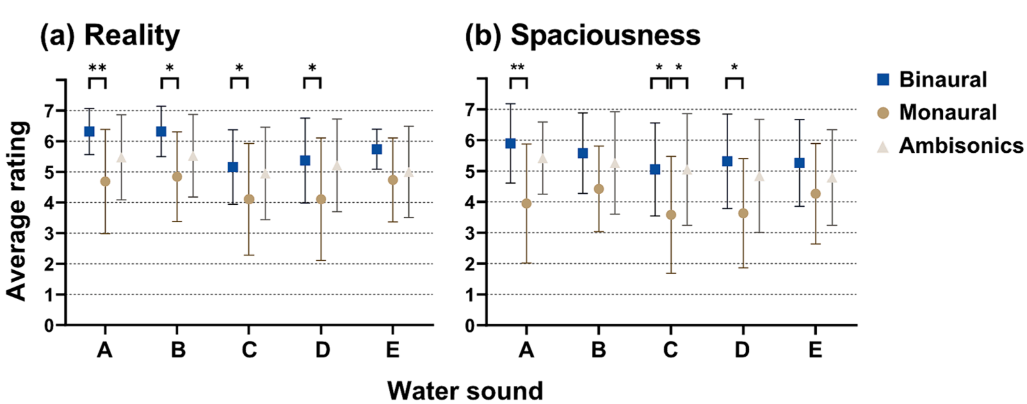

Fig. 7. Averaging rating scores of the reality (a) and spaciousness (b) across participants. The markers represent the scores, while the error bars indicate the standard deviations. The * and ** symbols indicate significant differences at the level of 0.05 and 0.01, respectively.

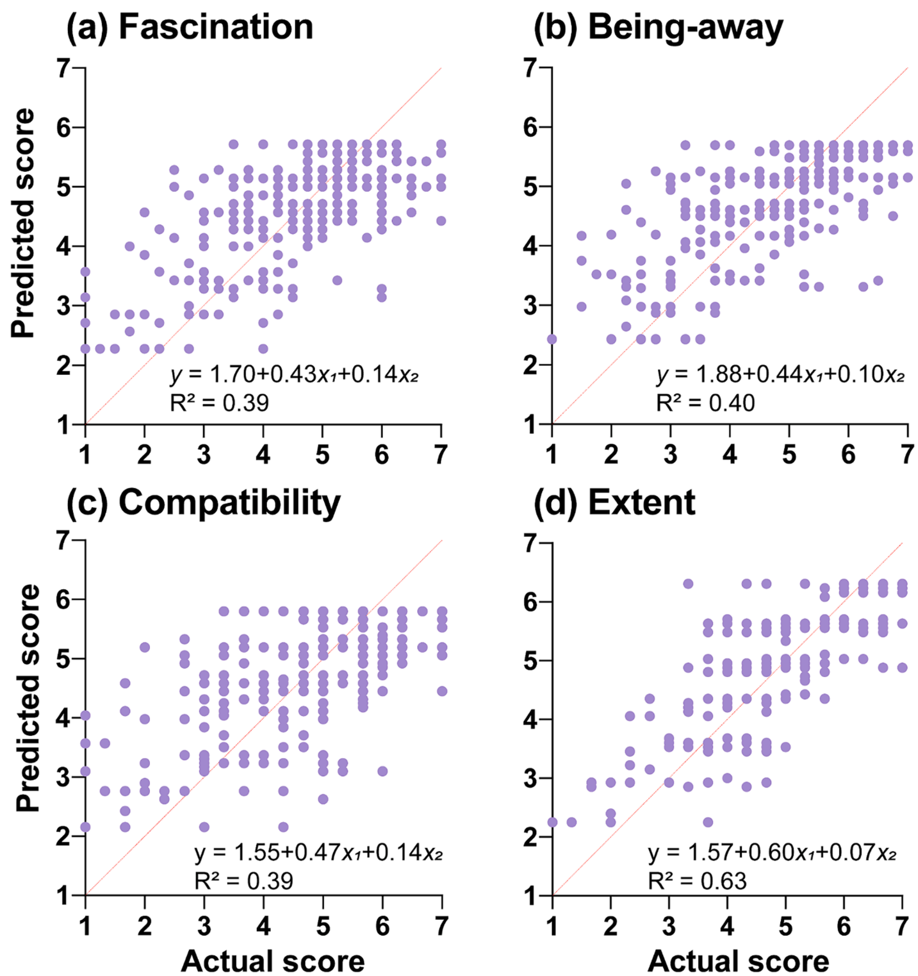

Fig. 8. Predicted scores using multiple linear regression as a function of actual recorded scores. The dependent variable y indicates scores of the fascination (a), the being-away (b), the compatibility (c), and the extent (d), and the independent variables x_1 and x_2 denote scores of the reality and the spaciousness, respectively.

system can reproduce, the higher the rating of reality and spaciousness the system will obtain. In this study, binaural and Ambisonics systems had a higher rating of reality and spaciousness compared with the monaural system. Hong compared direction (similar to spaciousness in this study) and realism (similar to reality in this study) ratings under soundscapes reproduced by static binaural, head-tracked binaural, and loudspeaker-based FOA, and they found loudspeaker-based and head-tracked binaural FOA superior to static FOA [22]. Xu and Kang also found a significantly higher rating on directionality and realism when comparing binaural and monaural reproduction [21].

The results of this study further demonstrate a significant correlation between reality and all four dimensions of the restoration effect. In contrast, the potential intrinsic connection between spaciousness and the restoration effect was more delicate. Therefore, current results do not underline the importance of the spatial distribution of elements in soundscapes. Previous studies have proved a significant correlation between the realism of virtual soundscapes and overall soundscape perception [21], but the restoration rating was not investigated in their study. These findings further suggest that future research on the soundscape psychological recovery effects should focus on the realistic reconstruction of virtual soundscapes.

The dependence of reality and spaciousness on the extent dimension were pronounced than on the other dimensions. The extent attribute of ART requires that the environment should be rich and coherent enough to constitute an entirely different world for individuals [1]. Concerning virtual audio display, the extent attribute intrinsically highlights the immersion of the virtual sound environment. In other words, the virtual soundscape must attain a level of realism that immerses listeners in a virtual sound world and ultimately enhances the restorative effect. In this study, monaural stimuli were reproduced diotically, which was expected to result in a limited sense of externalization and realism. This may explain why monaural stimuli achieved the lowest scores in terms of the recovery effect.

4.2. Different virtual audio systems

In this study, we investigated three virtual audio systems: binaural, monaural, and FOA systems. For nearly all water sounds and across all dimensions of the restoration effect, monaural system scores exhibited noticeable discrepancies compared to in situ cases. The study of Xu and Kang suggested that there is no significant difference between the binaural and monaural systems when considering the overall impression, acoustic comfort, pleasantness, annoyance, and eventfulness aspects of soundscape perception [21]. Nonetheless, our findings suggest that monaural system can bring nonnegligible deterioration to the psychological restoration effect of soundscapes, in contrast to the aspects of soundscape perception mentioned above. Monaural system with earphones cannot remain space distribution information of sound sources and circumvents the interference of head and pinnae on spectral, hence degrading the reality of virtual reproduced soundscape. The results imply the importance of the reality for the restoration effect, as mentioned in Section 4.1.

In general, binaural system obtained superior restoration effect scores and was closely analogous to in situ outcomes, compared to the other two virtual audio systems. Binaural recording and system can provide the highest space quality despite its limitations on usage and limitations [40]. Nevertheless, disparities persist between the scores of binaural system and in situ conditions, highlighting the constraints of current virtual environments.

The study of Guastavino compared the ecological validity of stereo and Ambisonics in soundscape perception [41]. This study extends the verification of the ecological validity of Ambisonics system for the restoration effect of soundscapes in comparison to monaural and binaural system. The spatial resolution of Ambisonics is constrained by its order (the number of microphones and loudspeakers limits order), resulting in inferior spatial precision compared to binaural system. Besides, FOA encounters the problem of spatial aliasing inducing spectral distortion in the high-frequency range [42]. However, significant differences between FOA and binaural system were only observed in a few instances, albeit the scores of FOA being slightly lower than those of binaural system for both restoration effect and reality/spaciousness rating. Given the versatile applicability of the Ambisonics, allowing for interactive virtual soundscapes, it is advisable to employ a spherical microphone to promote the Ambisonics order. This is assumed to further enhance the realism and psychological restoration effect of virtual soundscapes.

All three virtual audio systems, particularly monaural and FOA virtual stimuli, failed to consistently achieve recovery scores comparable to in situ conditions for waterfalls C and D. Sound contents-related variations of reproduction performance were also found in previous studies [22,23]. One of the possible reasons is that waterfalls contain more energy in the higher frequency range and have a larger loudness, which costs more attention resources. Previous laboratory experiments also suggested that listeners may not prefer waterfalls. Cai found that waterfalls have the weakest annoyance alleviation effect on noise [33]. Jeon suggested that participants preferred water sounds such as "stream" and "waves of lake" over waterfalls [43]. Several other laboratory experiments also suggested that waterfalls were less acoustic relaxation [44–46]. Interestingly, significantly lower recovery effect scores for waterfalls were not observed in the in situ experiment conducted in this study. The participants were likely to focus their attention on the sound in the laboratory experiment more than they did in the in situ scenes, since the experiment focused on rebuilding the sound environment of soundscapes. Further experiments may be necessary to delve deeper into the multimodal perception of the restoration effect. While the restoration effect may be affected by non-acoustic factors, this study advocates that the acoustic restoration effect differences of different types of water sound should be considered in the design of the garden. It may be advisable to avoid or scale down the large waterfalls of artificial hills, which are essential elements of Chinese classical garden construction, in areas designed for relaxation.

5. Limitations of the study

The number of participants is relatively small. Increasing numbers of participants could reduce the variation of rating scores and induce statistically significant in cases where the deviation is considerably large, e.g., a significant difference between Ambisonics and monaural systems at both four restoration dimensions and reality/spaciousness. However, for each soundscape location, the number of participants in this study fulfilled the estimated minimum requirement (17 participants, calculated with G*power 3.1).

Another essential limitation is that the PRSS used in this study was translated into English, and the validity of the translated questionnaire needs to be further investigated. During the experiment, the meaning of the questionnaire was interpreted by participants carefully. Although Cronbach's α of the overall result for fascination, being-away, compatibility, and extent were 0.89, 0.87, 0.86, and 0.80, respectively, which is relatively high, comprehensive research on Chinese PRSS validation is needed.

The present study compared restoration ratings under sound fields reproduced by monaural, binaural, and FOA methods. By using a more complicated recording and reproduction array, higher-order Ambisonics is promised to enhance the immersion of the virtual sound field. However, the technology was not involved and evaluated in the current study. Future work plans to evaluate the higher-order Ambisonics recording and reproduction in soundscape reproduction.

In terms of visual presentation, a regular monitor rather than a panorama video system was utilized in the experiment, thereby limiting the realism of the visual information. Although the current experiment primarily focuses on comparing the perception of acoustic restoration, higher fidelity visual information may further promote the ecological validity of the experiments.

6. Conclusions

This study focused on evaluating and comparing the psychological restoration effects of five water soundscapes from a Chinese classical garden, utilizing binaural, monaural, and FOA virtual audio systems, in comparison to their real-world counterparts.

Binaural system maximally retains the restorative effects of water sound, whereas monaural system may be unsuitable for replicating virtual soundscapes for recovery effect research. FOA also obtained comparable fidelity of the recovery effect with real soundscapes. However, it is worth noting that all virtual waterfalls exhibited an inferior restoration effect compared to both other virtual water sounds and their real counterparts. Ratings for reality and spaciousness are correlated with the restorative effect of virtual soundscapes, particularly in relation to the extent dimension of the recovery effect. In contrast to the spatial orientation of elements within virtual soundscapes, overall reality may play a more significant role in influencing the restorative effect of these virtual environments.

The results of the experiments affirm our hypothesis that the fidelity of reproduced soundscapes affects the psychological restoration effects. Hence, the importance of high-fidelity virtual acoustic environment was emphasized for studies of the restoration effect of soundscapes. Furthermore, the variation of psychological restoration effect in different water sounds should also be taken into account when designing gardens.

CRediT authorship contribution statement

Xian Shi: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Zhenyu Guo:** Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Yuezhe Zhao:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This research was funded by National Natural Science Foundation of China (grant number 52378098). We appreciate all participants who took part in the experiments.

Appendix. Contents of questionnaires

The questionnaire was presented to all participants in Chinese. The questionnaire was derived from the PRSS. Both English and Chinese versions were presented.

For the in situ and laboratory experiments, disagree (1) to agree (7)
(Fascination)
1. I find this sonic environment appealing 我觉得这种（些）声音很有吸引力
2. My attention is drawn to many of the interesting sounds here 这种（些）声音听起来很有趣勾起了我的好奇心
3. I am interested in exploring the sounds here 我有兴趣去探索这种（些）声音
4. I am engrossed by this sonic environment 我沉醉在这种（些）声音里
(Being-away)
5. This is a different sonic environment to what I usually hear 这不同于我平时听到的那些声音
6. When I hear these sounds, I can escape from the annoying things 当我听到这种（些）声音我感觉逃离了那些心烦的事
7. When I hear these sounds, I feel free from work, routine, and responsibilities 当我听到这种（些）声音我感觉可以从学习、工作和责任中解脱放松出来
8. I don't have to concentrate on hearing the sounds. 我不必保持全神贯注去听这种（些）声音
(Compatibility)
9. This sonic environment fits with my personal preferences 这种（些）声音符合我的个人喜好
10. I rapidly get used to hearing these sounds 我能很快的习惯这种（些）声音
11. Hearing these sounds hinders what I would want to do in this place 听到这种（些）声音妨碍了我想在这做的事
(Extent)
12. All the sounds I'm hearing belong here. 我听到的声音属于这里
13. I think the sounds here are in harmony with the current place 我认为这种（些）声音听起来与这个地方很和谐
14. The sounds make me feel like in a vast environment 这种（些）声音让我感觉这里的环境很广阔
For the laboratory experiments only, disagree (1) to agree (7)
(Reality)
15. I feel the reproduced sounds are very real 我感觉这种（些）声音的再现很真实
(Spaciousness)
16. I feel these sounds have a strong sense of direction 我感觉这种（些）声音具有很强的方向感

References

[1] Kaplan S. The restorative benefits of nature: toward an integrative framework. J Environ Psychol 1995;15:169–82. https://doi.org/10.1016/0272-4944(95)90001-2.

[2] Ulrich RS, Simons RF, Losito BD, Fiorito E, Miles MA, Zelson M. Stress recovery during exposure to natural and urban environments. J Environ Psychol 1991;11:201–30.

[3] Joye Y, van den Berg AE. Restorative Environments. In Steg L, de Groot JIM. (Eds.), Environmental Psychology, John Wiley & Sons, Ltd, Chichester, UK, 2018: pp. 65–75. https://doi.org/10.1002/9781119241072.ch7.

[4] Ratcliffe E. Sound and soundscape in restorative natural environments: a narrative literature review. Front Psychol 2021;12. https://doi.org/10.3389/fpsyg.2021.570563.

[5] Park SH, Lee PJ, Jung T, Swenson A. Effects of the aural and visual experience on psycho-physiological recovery in urban and rural environments. Appl Acoust 2020;169:107486. https://doi.org/10.1016/j.apacoust.2020.107486.

[6] Payne SR. The production of a perceived restorativeness soundscape scale. Appl Acoust 2013;74:255–63.

[7] Payne SR, Guastavino C. Exploring the validity of the perceived restorativeness soundscape scale: a psycholinguistic approach. Front Psychol 2018;9. https://doi.org/10.3389/fpsyg.2018.02224.

[8] Zhao W, Li H, Zhu X, Ge T. Effect of birdsong soundscape on perceived restorativeness in an Urban Park. Int J Environ Res Public Health 2020;17:5659. https://doi.org/10.3390/ijerph17165659.

[9] Guo X, Liu J, Albert C, Hong X-C. Audio-visual interaction and visitor characteristics affect perceived soundscape restorativeness: case study in five parks in China. Urban For Urban Green 2022;77:127738. https://doi.org/10.1016/j.ufug.2022.127738.

[10] Shu S, Ma H. The restorative environmental sounds perceived by children. J Environ Psychol 2018;60:72–80. https://doi.org/10.1016/j.jenvp.2018.10.011.

[11] Li Z, Ba M, Kang J. Physiological indicators and subjective restorativeness with audio-visual interactions in urban soundscapes. Sustain Cities Soc 2021;75:103360. https://doi.org/10.1016/j.scs.2021.103360.

[12] Jeon JY, Jo HI, Lee K. Psycho-physiological restoration with audio-visual interactions through virtual reality simulations of soundscape and landscape experiences in urban, waterfront, and green environments. Sustain Cities Soc 2023;99:104929. https://doi.org/10.1016/j.scs.2023.104929.

[13] Li Z, Kang J. Sensitivity analysis of changes in human physiological indicators observed in soundscapes. Landsc Urban Plan 2019;190:103593.

[14] Zhang Y, Kang J, Kang J. Effects of soundscape on the environmental restoration in urban natural environments. Noise Health 2017;19:65.

[15] Medvedev O, Shepherd D, Hautus MJ. The restorative potential of soundscapes: a physiological investigation. Appl Acoust 2015;96:20–6. https://doi.org/10.1016/j.apacoust.2015.03.004.

[16] ISO, 12913-2: 2018—Acoustics—Soundscape Part 2: Data Collection and Reporting Requirements, ISO: Geneva, Switzerland, 2018.

[17] Guo Z, Lu Y, Zhou H, Li Z, Fan Y, Yu G. Anthropometric-based clustering of pinnae and its application in personalizing HRTFs. Int J Ind Ergon 2021;81:103076. https://doi.org/10.1016/j.ergon.2020.103076.

[18] Xie B. Head-related transfer function and virtual auditory display. J. Ross Publishing; 2013.

[19] Zotter F, Frank M. Ambisonics: a practical 3D audio theory for recording, studio production, sound reinforcement, and virtual reality. Springer Nature; 2019.

[20] Shu S, Ma H. Restorative effects of classroom soundscapes on children's cognitive performance. Int J Environ Res Public Health 2019;16:293. https://doi.org/10.3390/ijerph16020293.

[21] Xu C, Kang J. Soundscape evaluation: binaural or monaural? J Acoust Soc Am 2019;145:3208. https://doi.org/10.1121/1.5102164.

[22] Hong JY, Lam B, Ong Z-T, Ooi K, Gan W-S, Kang J, et al. Quality assessment of acoustic environment reproduction methods for cinematic virtual reality in soundscape applications. Build Environ 2019;149:1–14. https://doi.org/10.1016/j.buildenv.2018.12.004.

[23] Ooi K, Hong J-Y, Lam B, Ong ZT, Gan W-S, Ooi K, et al. Validation of binaural recordings with head tracking for use in soundscape evaluation; 2017.

[24] Ratcliffe E, Gatersleben B, Sowden PT. Associations with bird sounds: how do they relate to perceived restorative potential? J Environ Psychol 2016;47:136–44. https://doi.org/10.1016/j.jenvp.2016.05.009.

[25] Hong J, He J, Lam B, Gupta R, Gan W-S. Spatial audio for soundscape design: recording and reproduction. Appl Sci 2017;7. https://doi.org/10.3390/app7060627.

[26] Uebel K, Marselle M, Dean AJ, Rhodes JR, Bonn A. Urban green space soundscapes and their perceived restorativeness. People Nat 2021;3:756–69. https://doi.org/10.1002/pan3.10215.

[27] Hedblom M, Gunnarsson B, Iravani B, Knez I, Schaefer M, Thorsson P, et al. Reduction of physiological stress by urban green space in a multisensory virtual experiment. Sci Rep 2019;9:10113. https://doi.org/10.1038/s41598-019-46099-7.

[28] Krzywicka P, Byrka K. Restorative qualities of and preference for natural and urban soundscapes. Front Psychol 2017;8:1705. https://doi.org/10.3389/fpsyg.2017.01705.

[29] Ma H, Shu S. An Experimental study: the restorative effect of soundscape elements in a simulated open-plan office. Acta Acust Acust 2018;104:106–15. https://doi.org/10.3813/AAA.919150.

[30] Jeon JY, Jo HI, Lee K. Potential restorative effects of urban soundscapes: personality traits, temperament, and perceptions of VR urban environments. Landsc Urban Plan 2021;214:104188. https://doi.org/10.1016/j.landurbplan.2021.104188.

[31] Alvarsson JJ, Wiens S, Nilsson ME. Stress recovery during exposure to nature sound and environmental noise. Int J Environ Res Public Health 2010;7:1036–46. https://doi.org/10.3390/ijerph7031036.

[32] Ratcliffe E, Gatersleben B, Sowden PT. Bird sounds and their contributions to perceived attention restoration and stress recovery. J Environ Psychol 2013;36:221–8.

[33] Cai J, Liu J, Yu N, Liu B. Effect of water sound masking on perception of the industrial noise. Appl Acoust 2019;150:307–12. https://doi.org/10.1016/j.apacoust.2019.02.025.

[34] Hong JY, Lam B, Ong Z-T, Ooi K, Gan W-S, Kang J, et al. The effects of spatial separations between water sound and traffic noise sources on soundscape assessment. Build Environ 2020;167. https://doi.org/10.1016/j.buildenv.2019.106423.

[35] Yuan X, Wu S. Soundscape of classical Chinese garden. Front Archit Civ Eng China 2008;2:172–8. https://doi.org/10.1007/s11709-008-0026-6.

[36] Staats H, Kieviet A, Hartig T. Where to recover from attentional fatigue: an expectancy-value analysis of environmental preference. J Environ Psychol 2003;23:147–57. https://doi.org/10.1016/S0272-4944(02)00112-3.

[37] Nachbar C, Zotter F, Deleflie E, Sontacchi A. AMBIX -A suggested ambisonics format; 2011.

[38] Zotter F, Frank M. All-round ambisonic panning and decoding. J Audio Eng Soc 2012;60:807–20.

[39] Solvang A. Spectral impairment for two-dimensional higher order ambisonics. J Audio Eng Soc 2008;56:267–79.

[40] Li H, Lau S-K. A review of audio-visual interaction on soundscape assessment in urban built environments. Appl Acoust 2020;166. https://doi.org/10.1016/j.apacoust.2020.107372.

[41] Guastavino C, Katz BF, Polack J-D, Levitin DJ, Dubois D. Ecological validity of soundscape reproduction. Acta Acust Acust 2005;91:333–41.

[42] Ward DB, Abhayapala TD. Reproduction of a plane-wave sound field using an array of loudspeakers. IEEE Trans Speech Audio Process 2001;9:697–707. https://doi.org/10.1109/89.943347.

[43] Jeon JY, Lee PJ, You J, Kang J. Perceptual assessment of quality of urban soundscapes with combined noise sources and water sounds. J Acoust Soc Am 2010;127:1357–66. https://doi.org/10.1121/1.3298437.

[44] Galbrun L, Ali TT. Acoustical and perceptual assessment of water sounds and their use over road traffic noise. J Acoust Soc Am 2013;133:227–37. https://doi.org/10.1121/1.4770242.

[45] Galbrun L, Calarco FMA. Audio-visual interaction and perceptual assessment of water features used over road traffic noise. J Acoust Soc Am 2014;136:2609–20. https://doi.org/10.1121/1.4897313.

[46] Patón D, Delgado P, Galet C, Muriel J, Méndez-Suárez M, Hidalgo-Sánchez M. Using acoustic perception to water sounds in the planning of urban gardens. Build Environ 2020;168:106510. https://doi.org/10.1016/j.buildenv.2019.106510.