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Improving informational-attentional masking of water sound on traffic noise by spatial variation settings: An in situ study with brain activity measurements

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ABSTRACT

According with soundscape strategies to improve the perception of the sound environment, laboratory studies have proven that introducing water sounds into urban spaces can be both an effective strategy for the informational-attentional masking of road traffic noise, and restorativeness creation. To extend previous laboratory findings and test the effectiveness and applicability of different spatial variations of water sounds in urban parks, a sound installation was prepared, and an experiment was conducted. Three different position-varied water-sound sequences were augmented into an existing University campus green park through surround sound design method with four Bluetooth loudspeakers. The mental effects and attention process were assessed by analyzing the EEG signals including aperiodic, oscillatory components and sensor-level functional connectivity, along with psychological scales. The water sounds played in-situ, brought more visual processing related to spatial attention and stimulus-driven salience. And the changes in the alpha band and the related theta/alpha ratio among four conditions showed more relaxation state induced by the introduction of water sounds, consistent with the positive effects on emotion saliency and perceived restorativeness. Moreover, different spatial variations of water sounds, especially for the two-position switching setting, modulated the activity of the attentional network related to the restoration process via the alpha-theta synchronization.

1. Introduction

1.1. Integrating water sounds into urban parks

Water features are commonly used in urban public spaces for multiple benefits, including visual appreciation, noise masking and recreational activity [1]. As a noise control strategy for its mitigation function, the introduction of water objects into noisy environments has been investigated in earlier works. Perkins (1973) observed the sound of water could mitigate the negative effects of traffic [2]. Booth (1989) [3], and Brown and Rutherford (1994) [4] started to investigate different water structures in landscape design for masking unwanted noise including still water structure, moving water structure, and fountains. Yang and Kang (2005) [5,6], and Yu and Kang (2008) [7] found human preference for water sound among natural sounds in noisy urban squares. The presence of water in both natural and built scenes was associated with higher preferences, higher pleasantness and higher perceived restorativeness than those without water [8]. The sounds of streams/rivers and fountains have shown strengthened effects on mitigating urban traffic noise [9–11], increasing auditory amusement [9–11], inducing mental relaxation [12], and enhancing perceived restorativeness [12]. More evidence has proven the positive effects of the water space on affective outcomes [13,14], life satisfaction [13,14], and restoration with mental health [13–15].

To investigate the effects of various acoustical characteristics of water sound on human perception in noisy environment, soundscape approach is quite adopted in recent years [9,16–19]. Soundscape was originally defined as “the quality and type of sounds and their arrangements in space and time” [20,21] and then has been extended to describe auditory perception of urban acoustic environment [22,23]. Many studies have tested various water features at different physical settings to optimize the soundscape quality and the desired sound levels to set the water sounds playback, such as the distance of water fountain [24], number of sound sources [25], type of water sounds

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(fountains/streams/water sculptures/waterfalls) [9,26,27], water spectral features [28,29], type of noise sources [30–32] and other environmental factors like landscape features [33], temperature [34] and so on. Jeon et al. (2012) found the sharpness of the water sound was a dominant factor for urban auditory perception, and water sound brought more description of "freshness" and "calmness" would lead to higher human preferences [28]. To be noted here, for the settings of signal-noise ratio between water sound and traffic noise, it is well-accepted that water sounds at levels 3dB lower than traffic noise could achieve better mitigation effects [9,30,35]. Besides, spatial organization also plays a role in auditory perception in acoustical environments. Evidence showed that spatial separations of water sounds and noise sources influence the perceptual assessments [17,36].

Soundscape approach provides the perceptual and emotional effects of wanted sounds in noisy environments like traffic noise, but more work needs to be done to reveal the internal interaction between the wanted sound and traffic noise in daily-life acoustical environments for landscape design and environmental promotion. Auditory attention is a cognitive process that modulate the perception of sound events / streams as well as control how we derive and interpret the natural acoustical events / streams of everyday life [37]. Cocktail party effect has been seen as a typical example of the listener's ability to derive information from one stream of speech in the presence of others in multi-talkers scenarios [38,39]. But not just related to concrete linguistic information, attention process has broader scope refers to perceptual or cognitive information in complex environment from the cognitive perspective [37]. Posner (1980) posited a distinction between two kinds of attentional orienting mechanisms, endogenous and exogenous. Because an endogenous cue relies on the use of information, it is thought to elicit top-down control, while the more primitive response to an exogenous cue is thought to be based on bottom-up processes [40,37]. As explained by Kaplan and colleagues' studies on the Attention Restoration Theory (ART), while voluntary attention requires cognitive efforts for its activation, sustainment, and to take distractions under control through inhibition, involuntary attention is more automatic and bottom-up stimulus-driven. In this sense, in realistic acoustical environment, the background noise of context plays an important role in activating or not our attention. In urban environments where people attempt to escape from road traffic noise, the latter acts as a bottom-up stimulus that triggers voluntary attention to overcome the unwanted noise. It is exactly the contrary of what happens in natural environments, where voluntary attention is not needed for the activation of the bottom-up stimuli, making them spaces rich in restorative power [41].

The attention re-orienting from unwanted sounds (like traffic noise) to the desired or "target" sound at a variety of levels in auditory perception is well-described by the term so-called "masking" effects. And the "masking" effects have been divided into two categories: "informational masking," and the complementary term "energetic masking" with which it is usually associated and contrasted, first appear in the auditory literature was a meeting abstract by Irwin Pollack from the Acoustical Society of America in 1975 [42]. The informational masking was firstly investigated through multi-tone masking experiment by manipulating the uncertainty of an element of a sequence of tones [43–45]. Then the concept has been widely used in speech field for understanding the speech processing with voluntary attention. Late Best et al. (2005) reported a study in which human listeners were trained to identify the calls of songbirds. They found spatial separation of target and masker sounds could alter masking effects through mechanisms that are not specific to speech [37,46]. More works have investigated informational masking with no-speech stimuli [47–49] with wider contexts related to auditory process including auditory object formation [50], sound source segregation [51], and auditory scene analysis [52,53]. Nowadays, studies of informational masking span a wide range of experimental stimuli and tasks as well as researchers believe that informational masking is the result of the actions of multiple stages of processing beyond the auditory periphery and is intimately connected to perceptual grouping and source segregation, attention, memory, and general cognitive processing abilities [37].

Until recent years, in agreement with the previous research, the mechanism of informational masking, also seen as "attentional masking" [54], originally applied on speech intelligibility (or at most to some verbal task) when the action of listening occurred in a noisy context, has also been tested, with success, to explore its use in helping to prohibit recognizing or understanding of unwanted sounds (e.g. traffic noise) [55] in everyday sound environments [46,56]. In particular, in the field research areas of the environmental acoustic and soundscape several scholars [57–59] have highlighted the importance of the meaning associated with the perceived noise/sound in the appreciation of the soundscape, and on the key role of attention. The main applications of informational-attentional masking concern the use of nature's sounds (fountains, waterfalls, water streams and birds) below the road traffic noise level which were used to improve the perceived urban sound quality [26,28,30,54,10,60,31,61,62].

1.2. Real field neural-psychological measurement

To measure the psychological outcomes of real-field sound environments on human responses and mental health, various semantic scales were developed based on different principles and protocols. Most used items can be sourced from the circumplex model of the Swedish Soundscape-Quality Protocol (SSQP), characterizing the perceived quality from eight items including pleasant, chaotic, vibrant, uneventful, calm, annoying, eventful, and monotonous [63,64]. The Perceived Restorativeness Soundscape Scale (PRSS) [65] is also quite used for assessing psychological restoration effects of soundscapes based on the Attention Restoration Theory (ART) [66,67]. Masullo et al. developed and compared two different questionnaires focused on assessing the emotional salience of sounds. The first questionnaire was built from the circumplex model of soundscape perception, whereas the second was constructed from emotional dimension of sounds. The results showed that the latter questionnaire revealed the positive and negative dimensions of the sounds more reliably and clearly than the first [68]. More works are still needed for clarifying the impact of sonic environment on human through oral reports.

The development of wearable sensing technology provides more opportunities to unveil the multifaceted influences of real environments on human minds and behaviors. Compared to the post-hoc oral reports, the greatest strengths of electrophysiological measurements of human neural responses are objective and reliable to the external environments. Those neuroscience tools reveal neural mechanisms underlying cognitive and emotional processes elicited by the exposure to different urban built and natural spaces, which could provide scientific evidence for policy-making on improved urban mental health [69,70]. Electroencephalogram (EEG) is a widely adopted technique advantaging from non-invasive and direct measures of neuronal activity [71]. Various studies have investigated the neural effects of real-field natural or built environments with their soundscape qualities on the human mind and mental health through EEG measurements [72–76]. Those studies have tried to connect the positive effect of natural elements with the patterns of the alpha band, which was considered a neural indicator of relaxation and comfort state. However, rather than changes in the alpha band, changes from the theta [74], beta [73,77,75,76] and gamma-band [75] were observed, which were inconsistent with image-based studies [78–80]. Moreover, the ratios of different frequency bands were also investigated for detecting concrete mental state, including stress, emotion, mental fatigue, cognitive workload etc. [81]. Few cases, however, have referred to blue spaces or acoustical aspects among those in-situ neural-psychological investigations of natural environments. Li et al. compared the soundscape components and EEG reactions in typical mountainous urban parks. The results showed that the relative power of the alpha band was more evident at the birdsong-dominant site than at the traffic-noise-dominant site, under both the audio-only and audio-visual conditions. Besides, more restorative EEG reactions were found within the audio stimuli than within the audio-visual stimuli [82]. And Koivisto et al. found stronger activity in the lower alpha band in the nature sound scenario than in the industry ones [83].

Not just as neural indicators of perceived environments, but electrophysiological measures can also shed light on the processes of auditory attention linked to noise masking. From the field of speech processing, the changes of whole-brain functional networks were used to decode the attention orientation of auditory streams [84,85]. Other study tried to use the EEG response for brain-computer interface application to detect locked-in syndrome (LIS) patients' auditory attention through the ERP paradigam called auditory steady-state response (ASSR) [86]. In real urban scenarios, Chen et al. (2020) compared the neural responses and psychological assessments of affective and cognitive functioning when participants were exposed to a restorative garden and traffic noise environment to explore the neural mechanism of environmental restorative experiences. They found stronger and more efficient alpha-theta synchronization during restorative experience indicating the induce of fatigue recovery, as well as stronger alpha-theta oscillations in the occipital lobes linking to attention restoration [87]. This methodology provides the potential to interpret the fundamental mental processes induced by the mask sounds in noisy environments regarding acoustic comfort, health, and well-being to enable policymakers and designers to extrapolate solid results.

1.3. Study purpose

To extend the applications of the introduction of water sounds into noisy environment, more design features are needed to consider. In real life scenarios, water fountains in urban parks are already demonstrated diverse spatial characteristics for aesthetic appreciation and recreation activities [88–90]. Inspired by previous works, we take spatial variation setting of water sound into account, assuming they could improve the perceptual attention of water sounds and cause better mitigating effects. Our previous online and laboratory studies showed more restoration state induced by water sound sequences from the EEG measurements including the alpha band power and alpha-beta power ratio. And the spatial variations of the water sounds, especially for the setting of two-position switching water, brought more attentional network activations than fixed position water sequences related to the information masking process along with positive feelings and perceived restorativeness. But lacking of visual contexts and multisensory environments, those results could be biased and further investigation are needed [91,92]. For practical consideration, introducing a real water infrastructure could be impossible for research purpose due to the difficulties from multiple aspects like space limitation, non-availability of water resource and high cost of infrastructure maintenance and so on. Learning from the works of practical designers and researchers by using digital methods like screen casting [93–95], loudspeakers playing [96–98] and interactive augmentation [99] in urban parks, augmented sound design was adopted for the introduction of water sound into urban park in the study.

This study used three different spatialized water-sound sequences played by four Bluetooth loudspeakers in an existing campus park to investigate their effects on informational masking of road traffic noise and restoration effects. Through Electroencephalogram measurements and psychological assessments, the general mental states revealed by the brain oscillation and attention restoration indicated by the brain connectivity network changes can help us discover the potential application of augmented sound design in landscape designing and noise controlling.

2. Method

2.1. Experimental design

Within-participants experiment designs were adopted for an in situ study. The Independent Variable (IV) was the spatial variation setting of water sounds played by four Bluetooth loudspeakers. Four levels of the IV included: Frontal position-fixed water sound (FPW); Two-position switching water sound (TSW); Four-position-randomized water sound (FMW); Road Traffic Noise only (RTN). TSW will include four different settings: frontal-left pair, frontal-right pair, back-left pair, back-right pair (frontal-back and left-right will be excluded to avoid distance differences of two-position pair).

The Dependent Variables (DVs) were the psychological assessments including general questionnaire about the characteristics of the sound environments [91], emotional saliency [68], Being-away and Fascination dimensions' items of PRS-11 [92] and the neural responses obtained by a wearable EEG device.

The hypotheses were: 1) Water sounds with spatial variations could evoke different attentional processes compared to traffic noise and promote more positive effects on mental states in a campus green space; 2) Compared to our previous laboratory environment, the spatial water sounds could bring more sensory accumulation and cause greater activation of brain activity in in-situ multisensory environment.

2.2. In situ set-ups

The site selected for the measurements of road traffic noise and the in-situ experiment was the open area on Podium adjacent to block Q inside the campus of the Hong Kong Polytechnic University (see Fig. 1). Facing the main road with heavy traffic noise in the district, the in-situ scenarios consisted of different kinds of flowers and trees in front of the sitting position of subjects, which could bring the visual inputs and more immersive context for human perception in urban parks. The test scenario was set as follows: subjects were sitting in the center of wide-open spaces facing the main road, and four Bluetooth loudspeakers (SONY SRS-XB23, SONY, Japan) were positioned at four directions (Frontal/Back/Left/Right) with same distances (1.2 m) to the subject sitting position (the height of loudspeakers were 21.8 cm). A sound level meter (SLM) (B & K 2270, Brüel & Kjær, Denmark) was set parallel to the sitting position (the height was set as 1.2 m) and the same distance to the nearest loudspeaker for real-time sound level monitoring of traffic noise (see Fig. 2). The playback of water sounds from the four Bluetooth speakers was programmed by the Pyo library, the sound pressure level (SPL) of produced water sounds was calibrated in the anechoic chamber ($6m \times 6m \times 3m$, background noise level < 15 dB(A)) of the Dept. of Mechanical Engineering of the Hong Kong Polytechnic University) before the experiment. During the experiment, the volume of water sounds played by each speaker would be controlled by python-based scripts to match -3 dB(A) to the SPL of traffic noise measured by SLM in real-time.

As mentioned in the experiment design part, four levels of spatial variations were defined as: Frontal Position-fixed Water sound (FPW), a Two-position Switching Water sound (TSW) and a Four-position-randomized Moving Water sounds (FMW), and empty water sound, all of them combined the Road Traffic Noise (RTN) on the frontal position as background. FPW was set as a fixed position of water sound in the frontal position with road traffic noise as background. As for TSW settings, four two-position pairs were defined: the frontal-right, right-back, back-left, and left-front pairs (only adjacent positions were considered for avoiding the distance differences of two-position pairs). The distance between each position soundtrack up to the subject was the same as FPW. For FMW, the pseudo-random routine of the water sound selected from four-position (frontal/back/left/right) was defined. Based on the results of our past research on the positive emotional effects [100,101] and noise masking effects [92,91] of stream water sounds

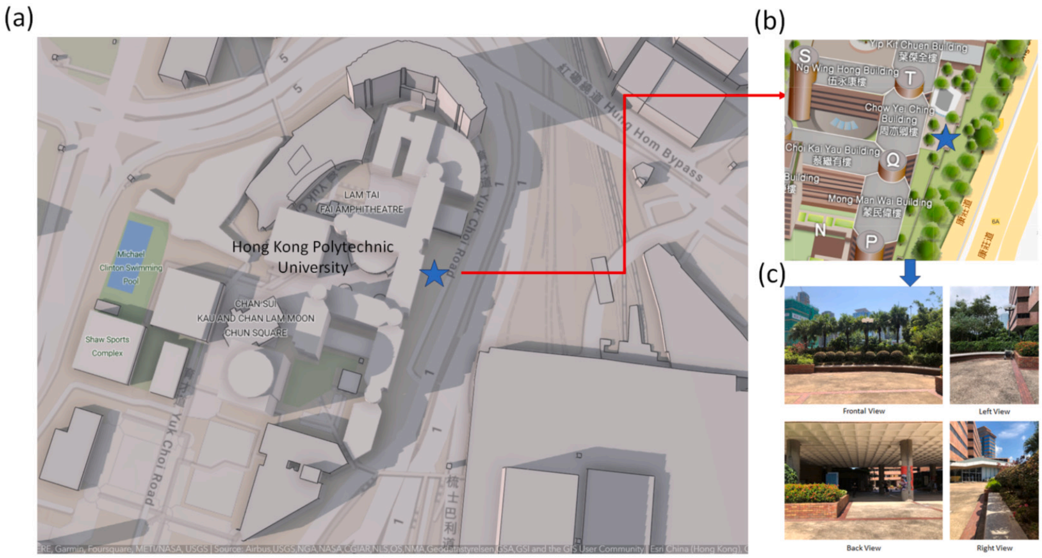


Fig. 1. The campus green park chosen for the in-situ experiment: (a) the google map of the selected campus park; (b) the isometric map of the test site; (c) the human perspective images from four directions of the test park.

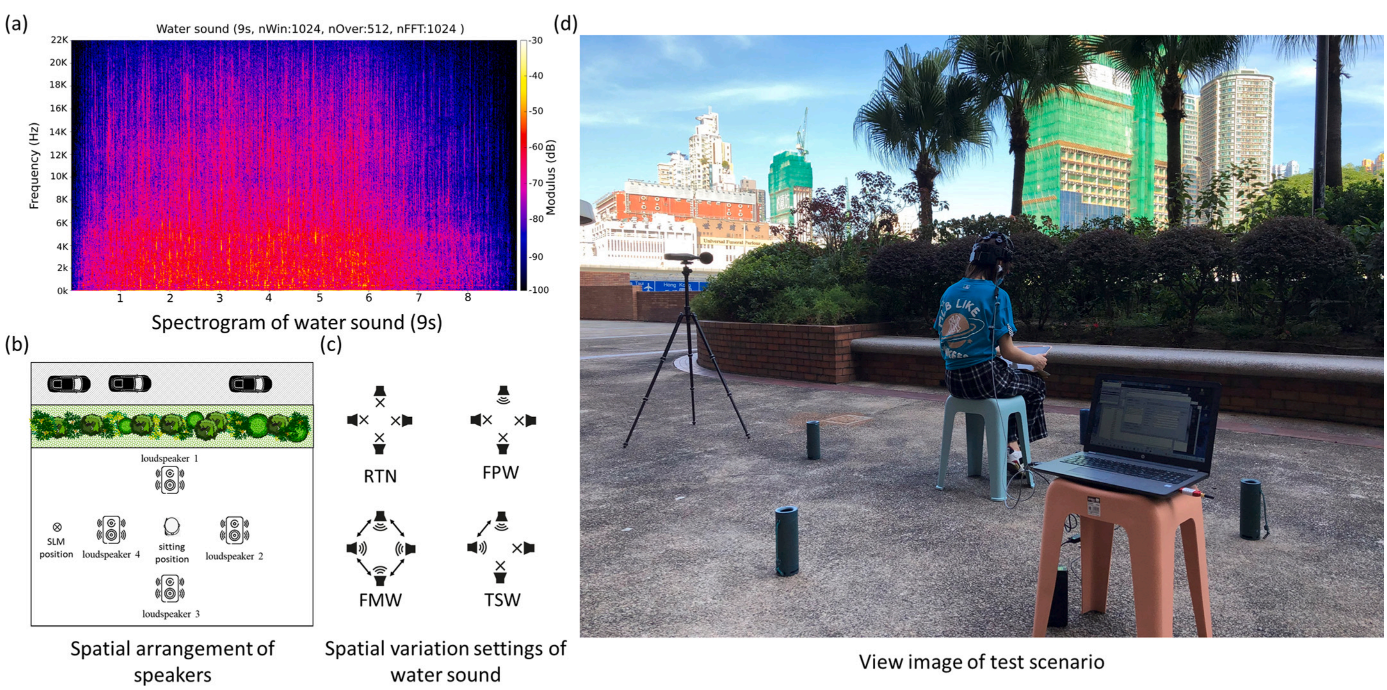


Fig. 2. The set-ups in the campus park for in situ test.

in urban parks, the type of water sound we chose was stream water, and two water-stream soundtracks were created based on the previous study [91], combined repeated 5 s of water stream sound (to assure the auditory stimuli have been fully processed and could trigger echoic memory based on previous studies [102–105]) with 2 s of fade-in and fade-out (see Fig. 2a, water stream sound was recorded by Zoom H6 Hand-Recorder device with Rode NTG – 2 microphone), alternating filling in the timeline with 2 s of overlap (see Fig. 3.).

Before the experiment, the sound pressure levels (SPL) of the RTN condition during the whole daytime period were measured by the B & K sound level meter in the test site as the references of the SPL settings of water sounds (see Fig. 4.). The relationship between the sound levels of water sound playback and the volume settings of the four loudspeakers was constructed by the sound level measurements of three-volume level settings (75%/85%/100%) in the anechoic chamber (space size: $6m \times 6m \times 3m$, background noise level < 15 dB(A), at the Department of Mechanical Engineering in the Hong Kong Polytechnic University) with same set-ups in in-situ test (the height of sound level meter was set as 1.2 m referenced from the normal ear height when sitting)(see Fig. 4.). To achieve the produced sound pressure level of stream water sound in the listener's position was 3 dB(A) lower than the SPL of recorded traffic noise, we also tested different distance settings of the four loudspeakers to the listener position, and at the end we chose the distance of 1.2 m for ideal distance setting. During the experiment, B & K sound level meter was also used to record the SPL of the environment. Notably, the SPL measured during the RTN condition was used as baseline for the volume setting of the water sounds to matching -3 dB(A) to the SPL of traffic noise.

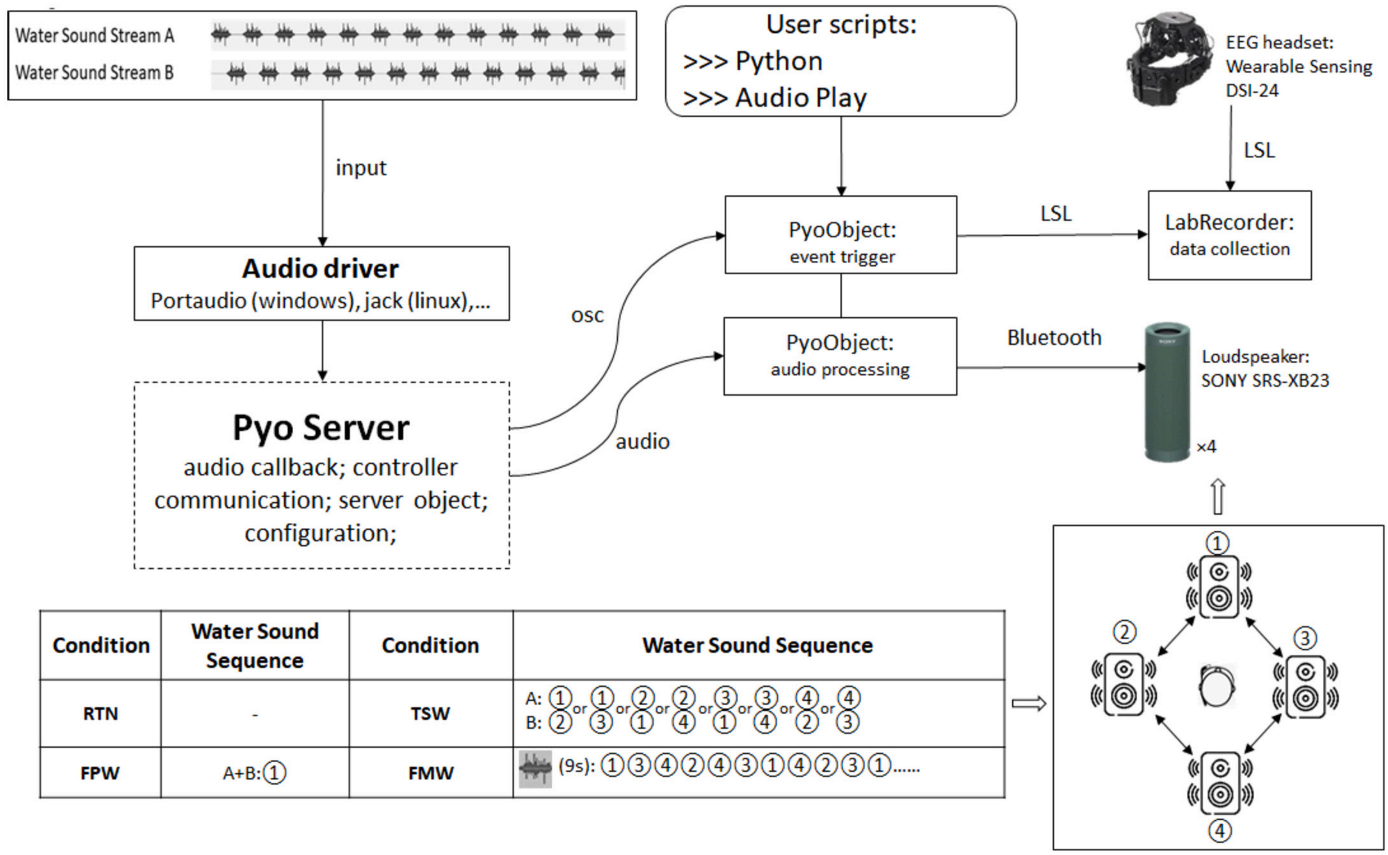
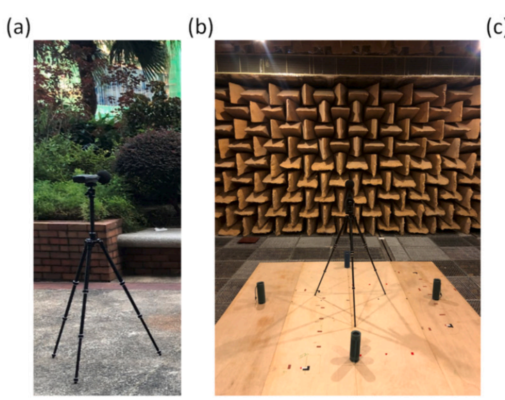


Fig. 3. The audio materials for the experiment and their configurations through Pyo library.



Traffic noise level at daytime before the test:
LAeq: 65.18
LA10.0: 66.68 LA50.0: 64.58 LA90.0: 63.01

Condition \ Volume settings	75%	85%	100%
FPW	57.60	62.50	68.94
FMW	57.55	62.40	68.41
TSW	57.57	62.41	68.40

Fig. 4. The acoustical measurements of traffic noise in the test site (a) and water sounds playbacks from the loudspeakers (b) with different volume settings and the measured sound pressure level (LAeq) data (c) in an anechoic chamber.

2.3. Experiment procedure

Twelve subjects gave informed consent and were instructed to sit in the chosen site of the campus park. Before the formal experiment, the subjects completed the initial set of questions in the questionnaires, containing basic information such as age (Mean age: 23.8; st.dev.: 5.0), gender (Male: 5; Female: 7), working environment, Weinstein Noise Sensitivity Scale [106] (Mean score: 3.3, st.dev.: 0.7), and Positive and Negative Affect Schedule (PANAS) [44] (Positive score: 20.7, st.dev.: 10.3. Negative score: 19.0, st.dev.: 10.2). After the preparation for the EEG headset (DSI-24, Wearable Sensing Ltd, USA) wearing and passing impedance check along with the starting of the sound level meter measurements, subjects were told to close their eyes for 3min relaxing. Then the formal experiment proceeds as showed in Fig. 5: (1) 3-min-long traffic noise-only open-eye listening (RTN); (2) psychological questionnaires answering; (3) 1-min-long interval for breaking; (4) repeating foregoing steps (1-3) with different spatial setting of sounds for four times (one for FPW, FMW separately, two TSW conditions were randomly selected from the four TSW conditions). The psychological questionnaires were presented online http://braincoder.io/spatial_sound/in_situ/ through a tablet (Apple iPad Air 3, Apple, USA) with the advantage of randomized items inside each scale. Finally, the subject took another 3-min rest with his/her eyes closed. The orders of four water sound conditions were balanced between subjects. The neural activities of two eye-closed periods were used for baseline correction for EEG analysis. The Ethical Committee for Scientific Research of the Department of Architecture and Industrial Design at the Università degli Studi della Campania "Luigi Vanvitelli" approved the protocol (documented in the department by the Ethics Committee of the department with the code 2021CERS03).

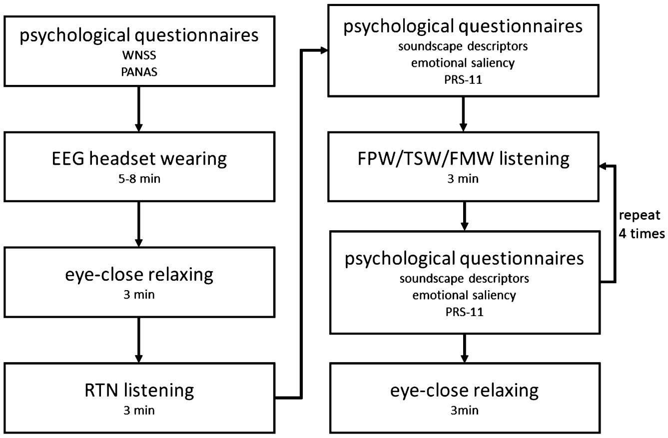


Fig. 5. The experiment procedure.

2.4. Data pre-processing and EEG analysis

The continuous EEG data were imported into MATLAB and EEGLAB toolbox [107] and pre-processed using the automated PREP pipeline for data cleaning [108]. One subject was excluded because of less clean data (the percentage of invalid data of that subject was higher than 50%). Then a 1-45 Hz band-pass filter was applied. After re-referencing the EEG signal to the average (except for A1 and A2 mastoid electrodes), their independent components were calculated using the Infomax algorithm [109]. Eye-blink and ocular movement artifacts were deleted based on the standard topographic profiles of the individual components and the distinctive temporal pattern. After the removal of eye-movement artifacts, the EEG data of each subject during each condition were extracted.

The cleaned EEG data were analyzed using MATLAB EEGLAB toolbox [107]. The power spectral density (PSD) of each electrode in each condition was computed by the "spectopo" function in EEGLAB. EEG signal could be decomposed into periodic (oscillations) and aperiodic (offset, exponent) signals [110]. Aperiodic component can be characterized by a $y + 1/f^x$ function, where y is the offset parameter, reflects the uniform shift of power across frequencies, and the x parameter, referred to the pattern of aperiodic power across frequencies of the PSD. The periodic components and aperiodic components of PSD were computed by the Irregular-Resampling Auto-Spectral Analysis (IRASA) method [111] referencing the code from the open-source tool Yasa [112]. As for the oscillation analysis, the mean powers of each frequency band (delta band was defined as the range of 1 to 4 Hz; theta band: 4-8 Hz; alpha: 8-13 Hz, beta: 13-30 Hz, low-gamma: 30-45 Hz) were extracted from the PSD of each electrode. The relative power of each electrode of each frequency band was calculated by dividing the given band power with the sum of full-band power (from 1 to 45 Hz). The interested electrodes were divided into five regions: the frontal (Fp1, Fp2, F3, F4), left temporal (F7, T3, T5), central (Cz, C3, C4), right temporal (F8, T4, T6) and posterior regions (P3, P4, O1, O2), respectively. The relative power for each band and the power ratios for different frequency bands were averaged in each region. The ratios of power for different frequency bands in each electrode was also computed for related frequency band ratios, including P(delta)/P(theta), P(theta)/P(alpha) and P(alpha)/P(beta), then were grouped into same defined regions.

Because of the limited number of electrodes of the EEG headset we used, EEG sensor-level connectivity analysis was conducted for network coherence analysis. Lacking the source information of concrete brain neuroanatomy locations leading to brain functional connectivity, five regions defined in EEG spectral analysis were also used for representing the temporal changes of functional networks of the brain in regional scale (referring to frontal, occipital, parietal, and temporal lobes). The 3-minute EEG data during each sound condition were epoched by 7 s fixed length and analyzed by MNE toolbox using spectral connectivity algorithm [113]. The spectral connectivity was computed for the debiased weighted Phase Lag Index (dwPLI). dwPLI is a debiased estimator of the squared wPLI developed by Vinck et al. [114], correcting for sample-size bias in phase-synchronization indices.

3. Results

3.1. Psychological assessments

The SPLs of the four conditions measured during the experiment were nearly the same ($F(4,32) = 0.778$, $p = 0.515$, $\eta^2 = 0.004$, $\eta_p^2 = 0.006$). And the traffic noise annoyances were decreased by the different settings of water sounds compared to the RTN condition, but the differences between water sound conditions were not statistically significant ($F(4,32) = 5.032$, $p = 0.006$ $**$, $\eta^2 = 0.098$, $\eta_p^2 = 0.314$). The two dimensions of the Perceived Restorativeness Scale (PRS-11) [115] items differed between traffic noise and spatial water sound conditions, and the highest scores were both in FMW condition (being-away: $F(4,32) = 3.763$, $p = 0.020$ $*$, $\eta^2 = 0.090$, $\eta_p^2 = 0.255$; fascination: $F(4,32) = 4.297$, $p = 0.012$ $*$, $\eta^2 = 0.074$, $\eta_p^2 = 0.281$) (see Fig. 6).

From the results of objective descriptors of each sound condition (naturalness, mechanicalness, smoothness, rhythmicalness, spaciousness, and familiarity) [91,92], most descriptors were distinguished between four conditions (see Table 1 for the ANOVA test results). Subjects felt more mechanical and less natural with traffic noise rather than water sound conditions, especially for FMW condition. And more rhythmic and smooth features were detected from FMW and TSW conditions than from traffic noise. Consider of the emotional feelings used the positive component (averaging from the scores of pleasant, attractive, stimulating, happy, energetic, calm items) of the emotional saliency's (ES+) and the negative component (ES−, averaging from the scores of unpleasant, unattractive, boring, sad, weak, nervous items) for evaluation [68,91,92], both emotional saliency (ES+/−) results indicated positive effects of all water sounds compared to traffic noise from the ANOVA post hoc test. But no significant differences between water sound conditions were found. Specifically, the main differences existed in two positive emotional items (calm/energetic) and three negative emotional items (unpleasant/unattractive/boring). All water sounds brought more calm effects and felt less unpleasant (especially for FMW condition). FMW and FPW condition were more energetic and less unattractive and boring than RTN condition (see Fig. 6 for post hoc comparisons).

3.2. EEG spectral results

The spectral offset differences of aperiodic component of PSD were particularly observed between different brain regions. Posterior region was significantly different from other regions under all conditions ($F(4,32) = 15.675$, $p < 0.001$ $***$, $\eta^2 = 0.185$, $\eta_p^2 = 0.201$). But there no significant changes among different acoustical conditions ($F(3,24) = 0.772$, $p = 0.521$, $\eta^2 = 0.026$, $\eta_p^2 = 0.035$). The interactions between sound conditions and brain regions suggested that the dissimilarity between brain regions of water sound conditions were greater than RTN condition ($F(12,96) = 2.250$, $p = 0.015$ $*$, $\eta^2 = 0.050$, $\eta_p^2 = 0.064$) (see Fig. 7). The spectral exponent of aperiodic component of PSD didn't change differently between RTN and water sound conditions ($F(3,24) = 0.757$, $p = 0.529$, $\eta^2 = 0.017$, $\eta_p^2 = 0.018$) or brain regions ($F(4,32) = 2.219$, $p = 0.089$, $\eta^2 = 0.035$, $\eta_p^2 = 0.036$). The periodic components of PSD both revealed remarkable reactions between sound conditions ($F(3,24) = 4.270$, $p = 0.015$ $*$, $\eta^2 = 0.080$, $\eta_p^2 = 0.096$) and brain regions ($F(4,32) = 7.120$, $p < 0.001$ $***$, $\eta^2 = 0.114$, $\eta_p^2 = 0.131$). The relative power of the delta/theta/alpha/beta bands all showed significant differences among four conditions in the whole brain. All water

Table 1
The statistical results of objective descriptors and emotional saliency between four conditions. The stars indicated the significance level of the ANOVAs results: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

Objective Descriptors					Emotional Saliency									
Items	F value	p value	η^2	η_p^2	Items	F value	p value	η^2	η_p^2	Items	F value	p value	η^2	η_p^2
Natural	3.065	0.042*	0.154	0.218	Pleasant	1.529	0.225	0.057	0.122	Unpleasant	8.133	0.000***	0.207	0.425
Mechanical	4.990	0.006**	0.110	0.312	Attractive	1.335	0.280	0.045	0.108	Unattractive	3.661	0.022*	0.139	0.250
Smooth	3.713	0.021*	0.070	0.188	Stimulating	0.341	0.796	0.010	0.030	Boring	3.735	0.021*	0.113	0.253
Rhythmic	8.782	0.000***	0.298	0.444	Happy	0.995	0.408	0.031	0.083	Sad	0.811	0.497	0.023	0.069
Spacious	0.064	0.978	0.004	0.006	Energetic	3.250	0.034*	0.056	0.228	Weak	0.778	0.515	0.031	0.066
Familiar	1.037	0.389	0.038	0.086	Calm	4.922	0.006**	0.144	0.309	Nervous	1.523	0.227	0.045	0.122
					ES+	2.935	0.048*	0.076	0.211	ES-	4.214	0.013*	0.126	0.277

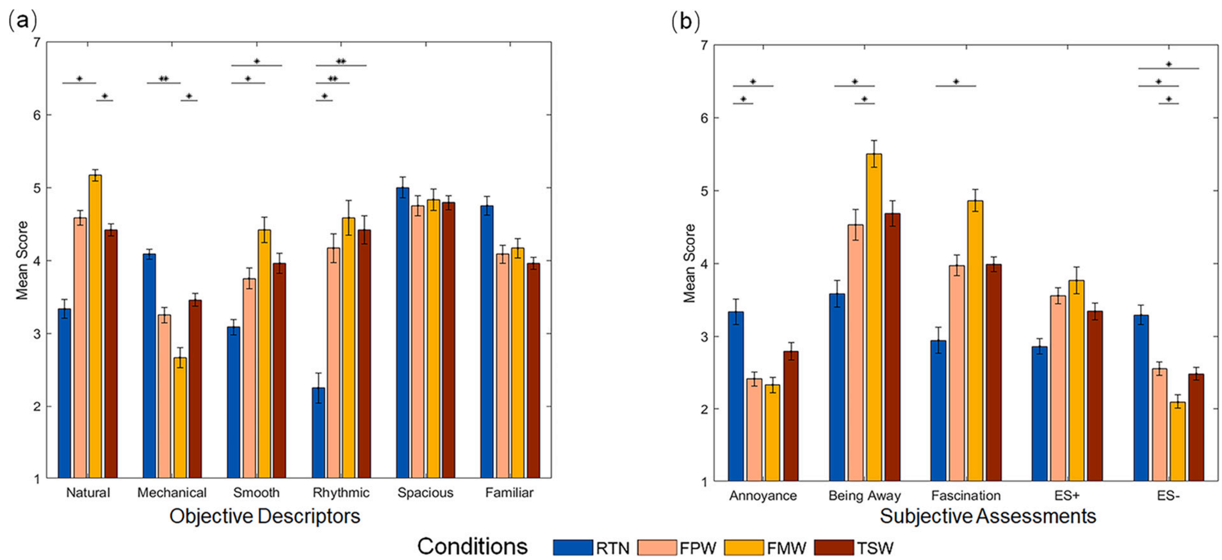


Fig. 6. The mean scores and standard errors of psychological assessments: (a) the objective descriptions between four sound conditions; (b) the subjective results related to noise annoyance, two dimensions of PRS-11, and the emotion saliency between four conditions. The stars indicated the significance level of the ANOVAs post-hoc results: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

Table 2
The statistical results of the spectral power of different frequency bands between four conditions from different brain regions. The stars indicated the significance level of the ANOVAs results: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

brain region	delta				theta				alpha			
	F value	p value	η^2	η_p^2	F value	p value	η^2	η_p^2	F value	p value	η^2	η_p^2
Frontal	6.636	0.001**	0.125	0.399	6.238	0.002**	0.190	0.384	8.469	0.000**	0.160	0.459
Central	9.227	0.000**	0.184	0.480	4.568	0.009**	0.130	0.314	8.758	0.000**	0.168	0.467
Left	6.442	0.002**	0.113	0.392	5.641	0.004**	0.166	0.361	7.429	0.001**	0.149	0.426
Right	9.533	0.000***	0.141	0.488	4.639	0.009**	0.149	0.317	8.908	0.000**	0.167	0.471
Posterior	8.095	0.000**	0.148	0.447	7.054	0.001**	0.190	0.414	8.490	0.000**	0.155	0.459
Total	8.209	0.000**	0.143	0.451	6.011	0.003**	0.176	0.375	8.844	0.000**	0.162	0.469

brain region	beta				gamma			
	F value	p value	η^2	η_p^2	F value	p value	η^2	η_p^2
Frontal	2.899	0.051	0.063	0.225	0.170	0.916	0.003	0.017
Central	6.634	0.001**	0.134	0.399	0.948	0.430	0.037	0.087
Left	3.434	0.029*	0.064	0.256	0.252	0.859	0.004	0.025
Right	6.765	0.001**	0.096	0.404	1.241	0.312	0.014	0.110
Posterior	5.371	0.004**	0.099	0.349	0.553	0.650	0.009	0.052
Total	5.004	0.006**	0.090	0.334	0.382	0.767	0.006	0.037

sound conditions had higher relative power of the theta, alpha and beta bands than RTN in the most of brain regions, but less relative power of the delta band (see Table 2 and Fig. 7 for post-hoc comparisons).

From the ANOVA test results, the index of delta/theta ratio showed significant differences between different conditions within each brain region except frontal position (see Table 3). From the post-hoc multiple pairwise statistical comparison, RTN ratios were not significantly higher than FPW, FMW and TSW in all of brain regions (see Fig. 8a). The index of theta/alpha ratio showed significant changes among different conditions within each brain region (see Table 3). From the one-way ANOVA analysis, the ratios of RTN were clearly higher than those of FPW, FMW, and TSW in all of the regions (see Fig. 8b). No significant difference of alpha/beta ratio was observed (see Table 3).

Table 3
The statistical results of the EEG indexes between four conditions with different brain regions. The stars indicated the significance level of the ANOVAs results: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

brain region	delta/theta				theta/alpha				alpha/beta			
	F value	p value	η^2	η_p^2	F value	p value	η^2	η_p^2	F value	p value	η^2	η_p^2
Frontal	3.455	0.073	0.125	0.204	4.521	0.010**	0.118	0.311	1.334	0.282	0.032	0.118
Central	3.455	0.029*	0.158	0.257	6.725	0.001**	0.189	0.402	0.926	0.440	0.015	0.085
Left	3.234	0.036*	0.144	0.244	4.221	0.013**	0.145	0.297	0.545	0.655	0.011	0.052
Right	3.152	0.039*	0.149	0.240	6.484	0.002**	0.165	0.393	0.484	0.696	0.009	0.046
Posterior	2.990	0.047*	0.128	0.230	4.993	0.006**	0.123	0.333	0.758	0.527	0.014	0.070
Total	3.073	0.043*	0.140	0.235	5.562	0.004**	0.147	0.357	0.838	0.484	0.016	0.077

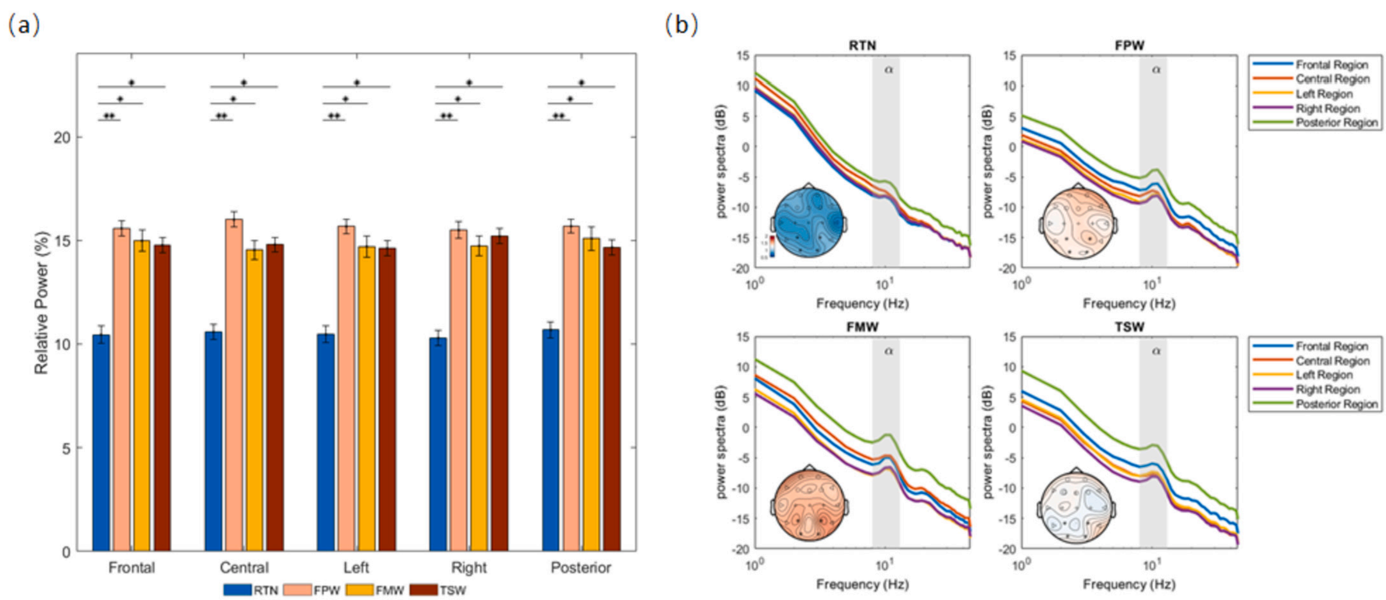


Fig. 7. (a) the average relative power (and standard error) of alpha-band across five regions between four conditions. (b) the power spectrum (in dB) of EEG across five regions between four conditions with topography of the alpha band. Stars indicated the significance level of the post-hoc ANOVAs results: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

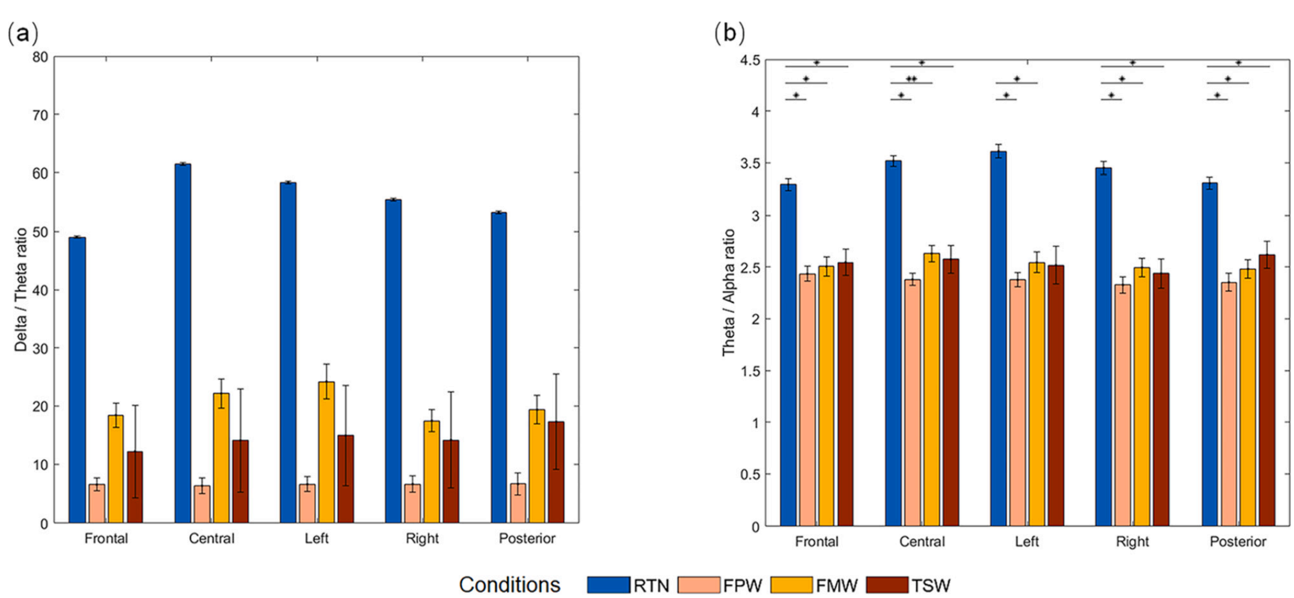


Fig. 8. The mean values and standard error of delta/theta ratios (a) and theta/alpha ratios (b) across different brain regions among four sound conditions. The stars indicated the significance level of the ANOVAs post-hoc results: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

Table 4
The statistical results of intra-/inter-regional connectivity between four conditions. The stars indicated the significance level of the ANOVAs results: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

Network	Brain region	delta		theta		alpha		beta		gamma	
		F value	p value	F value	p value	F value	p value	F value	p value	F value	p value
Intra regions	frontal	1.4925	0.2366	3.6328	0.0239*	1.3688	0.2712	0.2837	0.8368	1.0031	0.4050
	central	0.3659	0.7781	0.0278	0.9936	1.5719	0.2167	1.1691	0.3379	0.0580	0.9813
	left	0.8540	0.4756	3.3797	0.0310*	4.6156	0.0090**	4.9673	0.0065**	7.0218	0.0010**
	right	0.3912	0.7602	1.8957	0.1516	6.6199	0.0014**	1.8784	0.1545	0.3417	0.7953
	posterior	0.5025	0.6835	3.8078	0.0200*	2.0616	0.1264	2.4958	0.0788	0.6492	0.5896
Inter-regions	frontal-central	0.4004	0.7537	0.0936	0.9630	1.4531	0.2471	0.1524	0.9273	0.1471	0.9308
	frontal-left	0.4217	0.7388	4.3911	0.0112*	1.8038	0.1678	0.8422	0.4816	3.0285	0.0447*
	frontal-right	0.9658	0.4217	2.8922	0.0516	2.2519	0.1027	1.5826	0.2142	1.4573	0.2460
	frontal-posterior	2.6633	0.0659	4.2236	0.0132*	1.3693	0.2711	1.2282	0.3167	1.4621	0.2446
	central-left	0.9978	0.4073	1.0194	0.3979	2.4952	0.0789	0.2999	0.8252	0.4492	0.7197
	central-right	0.7420	0.5354	0.3033	0.8228	4.0646	0.0155*	1.5058	0.2331	0.1098	0.9537
	central-posterior	0.2340	0.8720	0.5529	0.6502	1.7258	0.1828	1.3036	0.2914	0.1256	0.9442
	left-right	0.2289	0.8755	2.9389	0.0491*	7.0102	0.0010*	0.6426	0.5936	1.2466	0.3103
	left-posterior	0.4932	0.6897	3.3127	0.0332*	3.8607	0.0190*	2.2195	0.1064	3.8302	0.0196*
	right-posterior	1.9299	0.1460	2.6306	0.0682	5.8032	0.0030**	1.5446	0.2234	0.4464	0.7216

Table 5
The significant results of post hoc multiple pairwise statistical comparison. The ↑/↓ indicated the column condition had higher/lower value than the compared condition.

Frequency Band	Network	Brain Regions	Compared Condition	RTN	FPW	FMW	TSW
theta	Intra-region	Left	RTN	–	–	–	↑, p = 0.007
		Posterior	FMW	–	–	–	↑, p = 0.031
	Inter-region	Frontal-Left	FMW	–	–	–	↑, p = 0.037
		Frontal-Posterior	RTN	–	–	–	↑, p = 0.012
		Left-Posterior	TSW	↓, p = 0.040	↓, p = 0.026	–	–
alpha	Intra-region	Left	TSW	↓, p = 0.010	↓, p = 0.035	–	–
		Right	TSW	↓, p = 0.034	↓, p = 0.035	–	–
	Inter-region	Central-Right	TSW	–	↓, p = 0.027	–	–
		Left-Right	TSW	↓, p = 0.006	↓, p = 0.000		
		Right-Posterior	TSW	↓, p = 0.037			
beta	Intra-region	Left	TSW	–	↓, p = 0.001	–	–
gamma	Intra-region	Left	TSW	↓, p = 0.033	↓, p = 0.007	↓, p = 0.001	–
	Inter-region	Left-Posterior	TSW	–	–	↓, p = 0.037	–

3.3. EEG connectivity results

The dwPLI connectivity results showed significant differences between four conditions within local regions across frequency bands. In the theta band, the main changes were in the frontal, left and posterior position, while in the alpha band, they differentiated in the left and right region. The differences of the beta band and gamma band also existed in the left region. Meanwhile, the inter-regions connectivity metrics illustrated crucial changes across frequency bands. In the theta band, the connections in the frontal-left, frontal-right, frontal-posterior, left-right, left-posterior regions were significantly different among the four conditions. As for the alpha band, the connections in the central-right, left-right, left-posterior, right-posterior regions were significantly different. When it came to the gamma band, the inter-regions had large differences including frontal-left and left-posterior inter-regions. (See Table 4 and Table 5 for detailed information.) From the post hoc analysis of the theta band connectivity data, the coherence of the local posterior region and most inter-regions in RTN condition were significantly less than in FPW and TSW conditions. For the alpha band connectivity results, the connectivity of TSW conditions in the intra/inter regions were significantly greater than those of FPW and FMW, and the latter two were both higher than RTN condition (see Table 5 and Fig. 9).

4. Discussion

4.1. The noise masking effects of water sounds on psychological assessments

The spatial settings of water sound (including TSW and FMW) improved the mitigating effects of traffic noise compared to FPW condition based on the subjective results, including noise annoyance, restorativeness qualities and emotional feelings. And the most varying position water sound, meaning the FMW condition, brought more positive emotional aspects consistently, implying the importance of the spatial arrangement of water design in urban park. Those in situ results were also consistent with the results from our previous online tests [91]. The positive effects of water sounds on perceived restorativeness were confirmed between online results and in situ results with the being-away and fascination components [91]. And the objective descriptors including natural, mechanical and smooth also showed highly consistent between the two studies [91]. Compared to our previous laboratory experiment [92], consistent results also indicated the similar emotional feeling responses caused by the spatial variation settings of water sounds, including energetic, boring, unpleasant, unattractive in those two laboratory [92] and in situ contexts. And the differences of other items like calm and stimulating between laboratory and real field experiment, could be caused by the contradictory settings between the spatialized sound and the absence of visual context. Therefore, the visual context

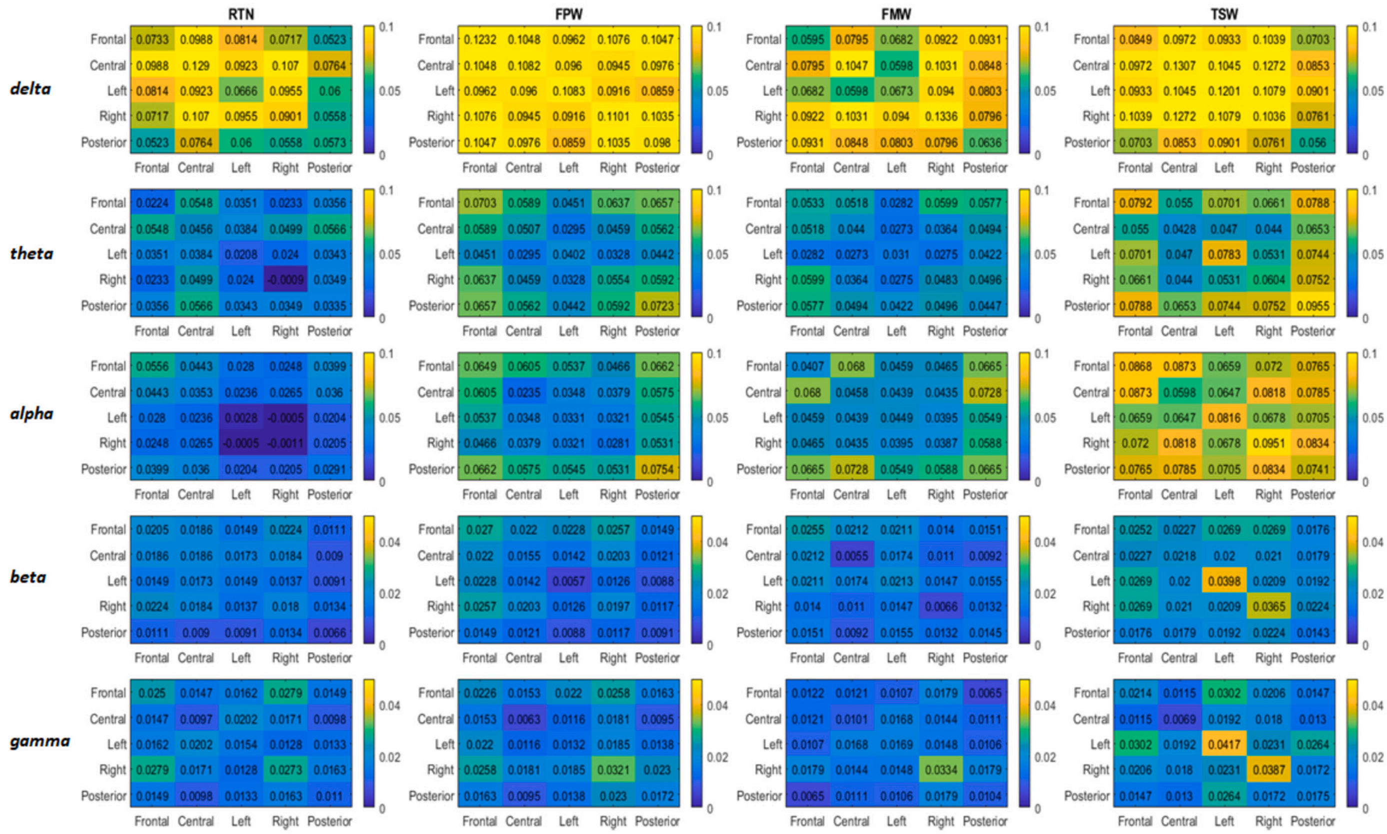


Fig. 9. The connectivity matrices of five brain regions for each frequency band and sound condition.

should not be ignored for the investigations of auditory perception and coherence design between acoustical and visual aspects for experiment efficiency should be valued for further studies and applications.

4.2. The mental states evoked by spatial settings of water sounds

Different aspects of mental states could be detected from various components of the EEG PSDs in our study. From the aperiodic offset components of each condition in our research, most activations from the occipital lobe of the brain were compared to those from other brain regions, meaning the ongoing visual-related information process [116] happened during each condition in real-field scenarios. And the more excitation in water sound conditions (especially for FMW and TSW) indicated the involvement of endogenous spatial attention and increased stimulus-driven salience [117] due to the spatial variations of water sounds. Although the flattened aperiodic exponent components in water sound conditions referring to the excitation/inhibition ratio of brain activity could not be distinguished from the RTN condition statistically, they were still noteworthy for the investigations of more multisensory scenarios and experimental settings in future researches [118].

The brain activities in the delta and theta band were contributed to parsing continuous acoustic streams into perceptual units in the studies of auditory perception [119,120]. Through the modulation of cortical entrainment to the sound envelope, those activities could track the acoustical rhythm [121,122] and organize acoustic information [123,119]. The related delta/theta band ratios were also found to represent the rhythmic perceptual sampling of auditory scenes [124]. The natural and regular water sounds masked the traffic noise and released those listening efforts based on the decrement of the delta power and delta/theta ratios based on the spectral and band ratio results. The higher relative powers of the alpha bands and lower ratios of the theta/alpha bands under spatial water sound conditions compared to the RTN condition, indicated more relaxation of the mental states induced by water sounds, which are also consistent with our laboratory research [92]. The theta/alpha ratio, often used as task load [125] of mental state, or mental fatigue [126], suggesting water sounds eased mental stress and fatigue caused by the background traffic noise. Moreover, the mental states induced by different water conditions did not differentiate from each other, same as aperiodic components and band ratios, indicating the spatial settings of water sounds did not influence the cognitive load or mental fatigue. Contrary to our previous laboratory experiments [92], the power of the beta band under water sound conditions were increased in parallel with the alpha band in the in-situ test. These changes could be contributed to the near-hand spatial arrangements of water sounds, which arousal more immersion states when subjects were experiencing the campus green space [127,128].

In summary, the power of the alpha band and the theta/alpha ratio were two robust indicators for detecting the relaxation of mental state under noisy environment based the consistent finding from our laboratory study [92] and other related studies [69,82]. But in the real field of urban park, more spectral changes including the aperiodic components correlated to visual perception, the delta and theta bands along with the delta/theta ratio could be related to auditory perception and the beta band reflecting immersion state were founded. The differences of the delta and theta oscillations between in-situ and laboratory studies could be caused by not only the added multisensory inputs in the in-situ study, but also the disparity of the characteristics of acoustical environments including the sound levels of the traffic noise and introduced water sounds. The sound level of traffic noise in the laboratory environment was 57 dB(A), while the sound level in the in-situ was 65 dB(A). The water sound levels were kept as -3 dB(A) below the traffic noise irrespective of laboratory or in-situ settings. The high frequency bands like the alpha and beta bands with related ratios, confirmed the positive effect of water sounds on traffic noise masking no matter of their spatial configurations. But lacking enough comparable evidence, more clarification of those results is still needed to draw solid conclusion. Therefore, further neuropsychological studies on human perception with various multisensory settings are needed to verify the mental implications of different aperiodic and oscillatory components from the EEG spectral results and build a ground truth about the interpretation of diverse neural responses for assessing the mental influences of different multisensory environments in urban green spaces.

4.3. The attentional restoration induced by spatial settings of water sounds

Developed by Rachel and Kaplan in the 1980s, the Attention Restoration Theory asserts that people can concentrate better after spending time in nature [66]. The theory explained the mental benefits of nature interaction based on the summary on literature that merged aesthetics and affective responses to environments as four restorative qualities including fascination, being away, coherence, scope, but left few descriptions about the mechanism underlying cognitive restoration and the implementation of restorative aspects of environments into urban context [129].

Attention process raises the activities of three independent brain functional networks: alertness (vigilance, arousal), orientation (between the dorsal network and the ventral network), and execution [130]. The dorsal network is related to involuntary attention in the superior parietal, occipital and frontal cortex electrodes. And the ventral network refers to the control of attention focus, voluntary attention in the anterior insula, temporoparietal junction, the anterior cingulate cortex and prefrontal cortex [131]. The level of alertness or arousal of attention was observed from the records of EEG oscillations since 1929. The phenomenon that the lower power in the alpha band with the increase of the delta band was well-known as an indicator of attentional engagement [132]. Since subjects were instructed to keep in resting-state in this study, the execution of attention for concrete tasks were omitted, although further studies with neurophysiological measurements could take advantage of this process to reveal more informational dimension about attention restoration. Therefore, the second attention process is the focus in this discussion part. Essentially, attention restoration characterizes the re-orientation of the attention process induced by external nature inputs, which is attracting the activation of involuntary attention and limiting the need for directed attention [133–136,86,137]. The changes of spectral components and functional connectivity of EEG signals from different brain regions reported by researchers like [138,139,87,140,141] provided clues to this fluctuating process. But more works are still needed to quantify this re-orientation process for measuring the restorative effects of real natural environments in real-time, which can help us to propose a more efficient operational definition about perceived restorativeness of different environments and promote more restorative features in practical urban landscape designing and managements.

In our study, the alpha band connectivities in all water sound conditions (FPW/FMW/TSW) were greatly stronger than in RTN condition, while the theta band connectivities only in TSW condition were significantly higher than in other conditions. Those results were also similar and extended with laboratory study [92]. Consistent evidence showed both connectivities in the alpha and theta band were related to attentional restoration [142,87]. Similarly, increased brain network statistics in the alpha-theta synchronization were observed during mindful meditation. Synchronization in the alpha rhythm could reflect top-down, inhibitory control processes [143], while that in the theta rhythm could reveal novel information encoding from external environments [142]. Thus, more restorative experiences were reflected by the responses of the alpha-theta synchronization network during the spatial water sound conditions especially for the two-position switching water sound condition.

5. Limitations and future studies

Certain limitations exist in the study. The number of participants is relatively small due to the COVID-19 situation during the period of in situ study, and future studies should include larger and more diverse participants for more solid conclusions. The limits of urban park scenarios also need to be noted. Different visual and acoustical environments in urban parks should be involved for improving the ecological validity of the research.

Although the wearable sensor technologies have developed greatly in recent years, the shortness of those measurements still needed more efforts to overcome. For EEG measurements, the sacrifices of limited channel and low signal-noise ratio for more portable setups should be noticed. More important thing is that those setups increase the discomfort for participant wearing while doing the experiments. This could influence participants' reactions and restrain the reliability of research outputs. Further studies with neural-behavioral measurements should be conducted with more advanced techniques to overcome those shortages.

To reveal the potential prospect of natural elements like water sounds for urban park design, the perceptual effects of urban parks involving noise mitigation, attentional restoration and emotional promotion should not be limited in resting-state of the participants. More physical states of urban park visitors and viewers should be explored, such as urban walking, urban biking, urban playing and so on. And more hybrid techniques for interactive designs between real-world environments and human are also necessary to explore deeper and multifunctional effects of urban parks with diverse augmented sound designs.

6. Conclusion

The introduction of water sounds could promote the positive effects on human health for urban park designing and managements. Using the digital water sound playbacks with different techniques like virtual sound production and surround sound system, the effects of spatial variations of water sounds were illustrated within existing urban parks with neuropsychological measurements. The multisensory inputs from the spatial water sounds in-situ brought more visual processing correlated to the spatial attention and stimulus-driven salience compared with laboratory environments. And the changes in the relative power of the alpha band and the ratio of the theta/alpha band among four conditions showed more relaxation state induced by the introduction of water sounds. Furthermore, different spatial configurations of water sound, especially the two-position switching setting, modulated the activity of attentional networks related to the restoration process via the alpha-theta synchronization network, reminding us of the importance of salience promotion by spatial organization for natural elements design like water sound design in urban parks.

CRediT authorship contribution statement

Jian Li: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Validation, Writing – review & editing. **Massimiliano Masullo:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Validation, Writing – review & editing. **Luigi Maffei:** Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. **Aniello Pascale:** Methodology, Resources, Software. **Chi-kwan Chau:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. **Minqi Lin:** Conceptualization, Data curation, Methodology, Software.

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.

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