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Using Spatial Water Sound Sequences for Traffic Noise Masking : Correlation Analysis of Subjective Evaluation and Neural Measurements

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ABSTRACT

Water-based masking sound has been proven effective on environmental noise control. But less is known about the effects and the process of the spatial configuration of water sounds on the perception of the surrounding environment. Through an immersive Spatial audio system, a virtual traffic noise environment base on an existing urban park was created in the lab. And three different spatial settings of water-sound sequences were added into the virtual acoustical environment to investigate the role of spatialization of water-sound sequences on traffic noise masking. The neural responses and subjective evaluations of twenty participants were collected with a portable electroencephalogram (EEG) device during the spatial sound playback time. The correlation analysis between subjective ratings and EEG indicators including spectral power, cognitive indexes and brain network connectivity were conducted.

The more positive effects on noise masking induced by the spatial setting of water sound sequences had been illustrated from the collinear relationship between the objective descriptors, the brain networks activities in the alpha band and positive emotional saliency scores.

Moreover, the spectral power of the gamma band and the theta alpha ratios used as the cognitive load index had showed a significant linear relationship with the negative emotional saliency.

Keywords: Water Sound; Noise Control; Spatialisation; Traffic Noise; EEG

1. INTRODUCTION

Noise pollution is a big concern for urban designers and landscape managers since it has been proven to impact public health physically and mentally (1). The introduction of natural sounds (e.g. water sounds, bird songs) into noisy urban environments has been treated as an effective strategy for noise reduction and abatement (2). Among them, water sounds are commonly used to mask traffic noise varying in its sound features (3). Many studies have tested various water sounds at different signal-to-noise ratios to optimise the soundscape quality and the desired sound levels to set the water sounds playback for noise mitigation (4–6). However, the spatial features of water sound are hardly discussed. Several studies have found that the spatialisation of sounds could improve the perceived sound quality (7,8) and spatial consciousness (8). Masullo and his colleagues (9) used Immersive Virtual Reality technology to investigate the effects of combining audio and visual elements of installations with water features on traffic noise mitigation in urban green parks. They confirmed the informational masking with water's sounds at levels 3 dB lower than the road-traffic background noise improved the subjective perception of the environmental quality of urban parks. Installations with water features improve their restorativeness on escaping and fascination components. They also compared the effect of the simulated and real water features on the restorativeness in urban parks. The results showed that water features simulated with audio-visual installations have significant positive effects on the Fascination and Being-Away components of restorativeness (10,11). Hong and others (12) explored the effects of spatial separations between target noise and water sound on perceived loudness of target noise and overall soundscape quality. The results indicated that the spatial separation between traffic noise and water sound can improve the overall soundscape quality and decrease the perceived loudness of the noise.

While there are already existed various studies about the neural responses of different urban space including green space (13,14), indoor environments (15–17), contemplative landscape (18) with perceived soundscape qualities, most of them used Electrophysiological (EEG) measures as neural indicators of sonic environments related to the comfort and restoration of individuals. But the cognitive process referring to auditory attention and noise masking and their relationship with perceived qualities and subjective responses has been less investigated. The changes of whole-brain functional networks have been used for indicating the process of the spatial attention in speech field (19) and emotion regulation in marketing researches (20,21). Szalárdy et al.(22) used functional connectivity of EEG signals between different brain regions to investigate the neuronal correlates of informational and energetic masking in a multi-talker situation. They found energetic masking was predominantly associated with stronger connectivity between the frontal and temporal regions at the lower alpha and gamma bands, and informational masking was associated with a distributed network between parietal, frontal, and temporal regions at the theta and beta bands. Our previous study (23) investigated the overall mental effects and attentional process of spatialized water-sound sequences related to informational masking of traffic noise through the spectral power and connectivity analysis of EEG signals. The results showed higher relative power of the alpha band and greater alpha-beta ratio among water sound conditions compared to traffic noise. And different spatial settings of water sound sequences induced different attention network changes. The two position switching water sounds brought more attentional network activations than other water sound sequences related to noise masking. But correlation between the mental processes induced by the mask sounds in noisy environments and soundscape qualities with corresponding emotional outcomes are remain unknown.

In this paper, water-sound sequences with different spatial settings were used to create a traffic noise environment base on an existing urban park. And the masking effects of spatial water sound on road traffic noise perception were investigated by correlation analysis of the neural responses and subjective evaluations collected from twenty participants. The correlation results could inspire the urban designer and policy maker to have more thoughts about urban soundscape design and noise control regarding acoustic comfort, human health and well-being.

2. METHODS

2.1 Experimental Design

A within-subjects experimental design was used. The independent variable (IV) was the spatial settings of the water sounds. Four levels of IV were defined: Frontal-fixed Position Water sound (FPW), a Two-position Switching Water sound (TSW) and a Four-position randomised Moving Water sounds (FMW), and no water sound (RTN), all of them combined the Road Traffic Noise on frontal position as background. The two-position pair of TSW included four spatial settings: frontal-left pair, frontal-right pair, back-left pair, back-right pair. Dependent variables (DV) were the neural responses collected by a wearable electroencephalogram device during each condition and subjective reports obtained by questionnaires at the end of each condition.

2.2 Sound Environment Settings

The sound sequences included a 3-minute traffic noise (LAeq: 65 dB(A), recorded by a Zoom H6 Hand-Recorder device with a Soundfield SPS200 microphone) as background noise (BGN), and a 5s water stream sound (recorded by a Zoom H6 Hand-Recorder with a Rode NTG-2 microphone). The sound equivalent level of the water stream sound was set at -3 dB with respect to the background traffic noise for optimizing noise masking. To match with the same duration of BGN, the water sound sequence combined repeated 5s of water stream sound with 2s fade-in and fade-out both ends, and then was cross-splitted to two streams with 2s overlap (see Figure 1-Temporal settings). They were played back within the Sens i-Lab, the multisensory laboratory of the Department of Architecture and Industrial Design of the Università degli Studi della Campania "Luigi Vanvitelli" through the Astro Spatial Audio, an object-based audio system (ASA) which drives 25 Adorn A55 Martin Audio and 2 Sx110 Martin Audio and rendered by SARA II Premium Rendering Engine. Two different kinds of sound source objects were used for the playback: a plane wave object, reproducing the wavefront of the sound propagation from road traffic noise, and a point source object, reproducing the water sound

(Figure 1-Spatial settings). The spatial location of each sound source for each condition was set as follow (Figure 1-Spatial Settings). The experimenter controlled the order of these sound sequences via browser-based GUI during the listening test. The listener was sitting at the centre of the test room of the Sens i-Lab, at about 3.5 meters from position of the virtual sound sources. The audio stimuli at listener's position were recorded using a dual channel system Sympnonie and an Mk1 Cortex manikin. They reproduced realistic auditory scenarios of the sound level about 57 dB(A), as those measured inside an existing urban park.

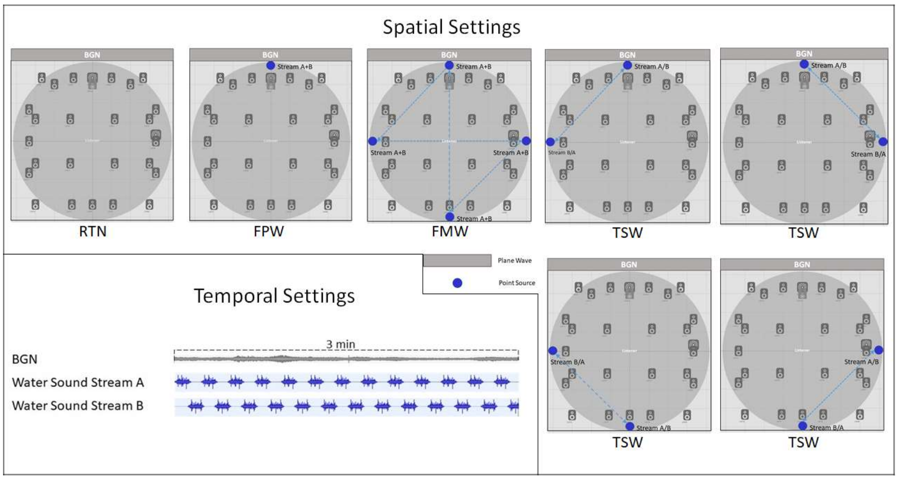

Figure 1-The spatial and temporal settings of the sound sources

2.3 Experimental Procedure

Twenty subjects gave informed consent and were instructed to sit in the center of the test room, being immersed in virtual sound environments. Before the formal experiment, the subject fulfilled two pages of the initial questionnaire, containing basic information such as age (average: 30; SD: 5.90), gender (Male: 12; Female: 8), working environment, and noise sensitivity (Weinstein Noise Sensitivity Scale) (24) (average score: 3.73; SD: 0.50). After wearing the portable EEG device and passing the impedance check of EEG electrodes, the subject was asked to listen to five sequences (two TSW condition randomly selected from four TSW conditions) with a comfortable sitting position and eyes open in the pre-defined balanced order. Each sequence lasted 3 minutes; then, the subject must fill a self-reported questionnaire. The first part of the questionnaire was focused on assessing general characteristics of the sound environment including naturalness, mechanicalness, smoothness, rhythmicalness, spaciousness, and familiarity, while the second investigated the emotional reactions of sounds. The latter part of the questionnaire combined items deriving from the circumplex model of soundscape perception with others focused on the emotional feeling of the sound environment (25). After finishing the questionnaire, the subject informed the experimenter to play the following sound sequence. Finally, the subject took 1-minute rest with his/her eyes closed. The neural activities during this period were used for baseline correction for EEG analysis.

During the whole process, the brain data of each subject were continuously recorded by DSI-24 wireless EEG headset with 20 dry electrodes signals referenced to Pz electrode at locations corresponding to the 10-20 International system (see Figure 2). The light and temperature in the lab were kept constant during the test. The EEG data were sampled at 300 Hz and streamed from the measurement device to the recording laptop using the Lab Recorder application based on the Lab Streaming Layer protocol (LSL) to synchronize the neural data with sound sequences. The Ethical Committee for Scientific Research of the Department approved the protocol.

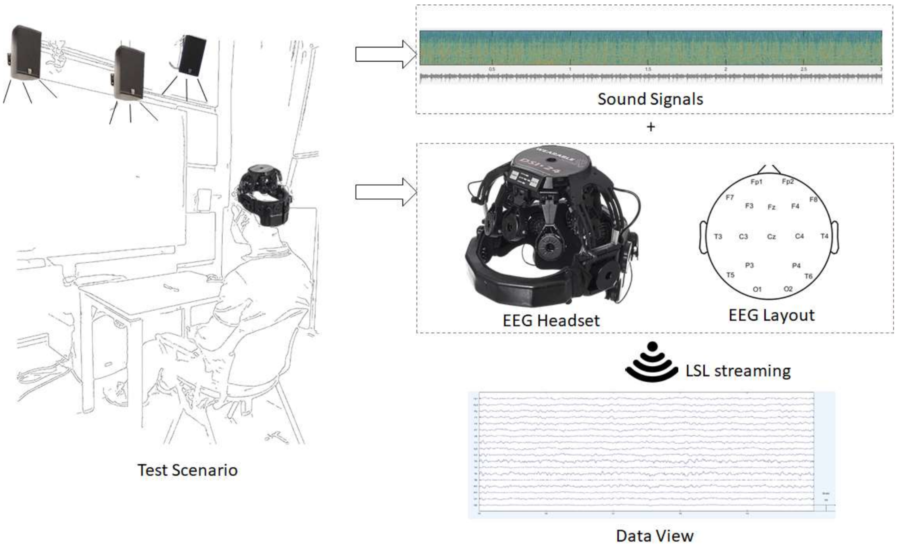

Figure 2-The experiment scenario of data collection

2.4 Data Analysis

The continuous EEG data were imported into MATLAB and EEGLAB toolbox (26) for data cleaning. The data of two subjects were excluded because of less clean data (both the percentage of invalid data were higher than 50%, the average of the valid data was 87.06%). Then a 1-45 Hz band-pass filter was applied for each subject's data. 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. Eye-blink and ocular movements 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 during each sound's perception for each subject were extracted.

The cleaned EEG data were analyzed using Matlab and FieldTrip toolbox (27). Time–frequency-resolved activities were obtained using the multitaper method (4 cycles width) based on Hanning sequences between 1 and 45 Hz (stepsize: 1 Hz), from which the average 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 derived. The interested electrodes were divided the interested electrodes 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 of each given band divided by the sum of power from 1 to 45 Hz was calculated as follow formula:

$$\boldsymbol{RP(f_1,\ f_2)} = \left[\boldsymbol{P(f_1,\ f_2)/P(1,45)}\right]\cdot \mathbf{100}$$

Where P(·) indicates the power, RP(·) indicates the relative power, and f_1, f_2 indicate the low and high frequency, 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 possible pairs of frequency bands, such as P(theta)/P(alpha) and P(alpha)/P(beta). The 3-minutes EEG data during each sound's condition were also epoched by 7s fixed length and analyzed by MNE toolbox (28) using spectral connectivity algorithm. 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.(29), correcting for sample-size bias in phase-synchronization indices.

3. RESULTS

3.1 Correlations between self-reported evaluations: objective descriptors and emotion responses

The scores of positive items' responses including pleasant, happy, stimulating, attractive, energetic, calm were averaged to compute the positive component of the emotional saliency's (ES+)(25). The correlation analysis showed as followed (Figure 3.a). The linear regression analysis between each objective descriptor (naturalness, mechanicalness, smoothness, rhythmicalness, spaciousness, and familiarity) of each sound condition and the ES+ were conducted (R^2= 0.452, F= 5.69, p<0.001). The significant regression coefficient was found in mechanical descriptor (β= -0.185, F= 9.456, p=0.003). And the linear relationship was also found between objective descriptors and negative component (ES-, averaged by the scores of boring, unpleasant, nervous, weak, sad, unattractive items)(25) (R^2= 0.374, F= 4.11, p<0.001) (see Figure 3.b for the correlation results). The significant regression coefficients were found in natural (β= -0.172, F= 4.871, p=0.031), mechanical (β= 0.269, F= 11.775, p=0.001), smooth (β= 0.205, F= 7.688, p=0.007) and rhythmic descriptors (β= 0.163, F= 5.560, p=0.022).

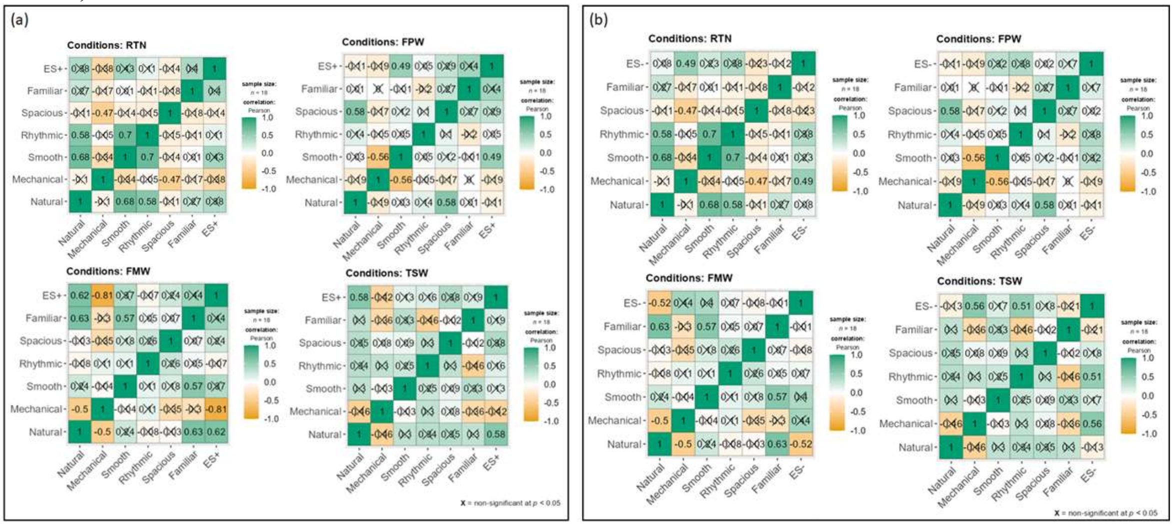

Figure 3-The correlation matrixes plots of objective descriptors with ES+ (a) and ES- (b) scores.

3.2 Correlations between the neural activities and self-reported emotional responses

The spectral power of the alpha band had a linear relationship with ES+ scores (R^2= 0.228, F= 2.330, p=0.029). The differences between four conditions were significantly observed (F=3.844, p=0.014). But the alpha power of each region had no significant relationship with ES+. The connectivity of the alpha band had a linear relationship with ES+ scores (R^2= 0.390, F= 1.88, p=0.039) especially contributed by the left-right regional connectivity (β= 9.290, F=5.105, p=0.028) (Figure 4a) and intra-right connectivity (β= -5.590, F=8.639, p=0.005) (Figure 4b). And the significant differences between each condition were also observed (F=2.889, p=0.044).

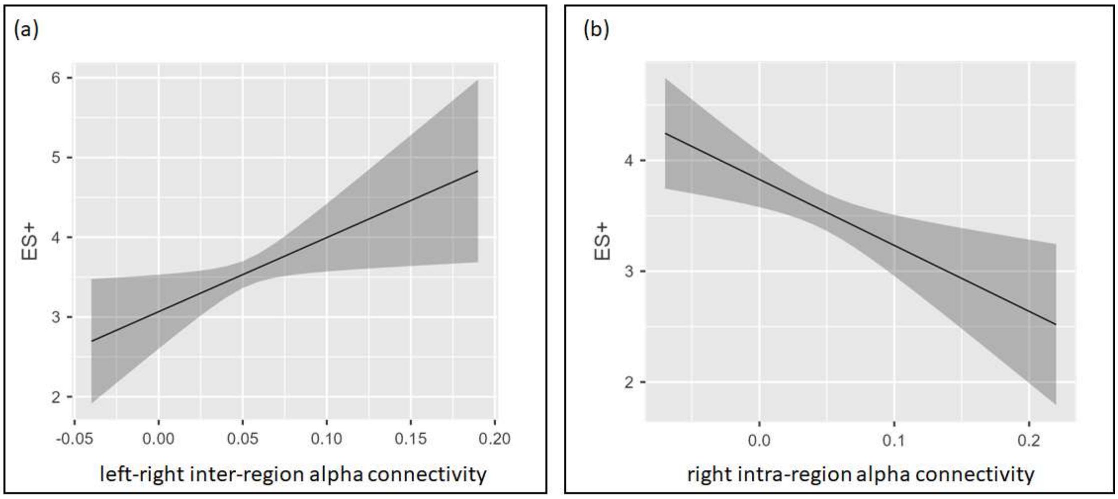

Figure 4- The linear plots of connectivity of the alpha band in left-right inter-region (a) and intra-right region (b) with ES+ scores

The theta alpha ratio index had a linear relationship with ES- (R^2= 0.290, F= 3.22, p=0.004). Especially the theta alpha index of right region had a significant relation with ES- (β= -2.853, F=4.602, p=0.036) (see Figure 5.a for the correlation results). But the differences between each condition were not significant. The spectral power of the gamma band also had a strong connection with ES- scores

(R^2= 0.438, F= 6.13, p<0.001). Among each region, the gamma power of the central and posterior regions indicated inversed linear relationship with ES- (β=11.840, F=15.140, p<0.001; β=-17.592, F=34.719, p<0.001) (see Figure 5.b for the correlation results). But the differences between each condition were not significant.

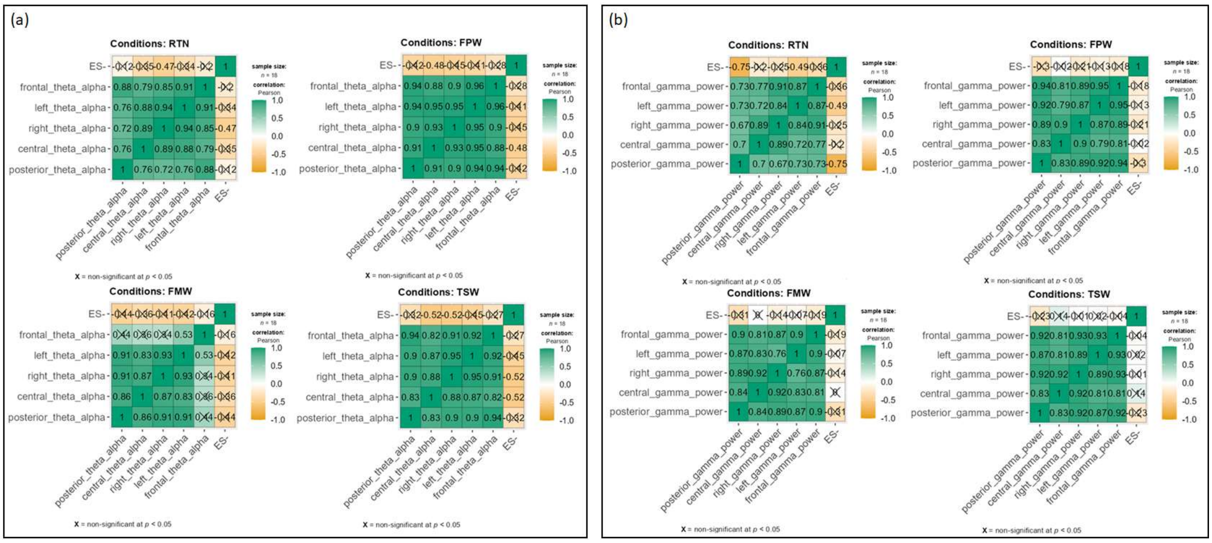

Fig. 5. The correlation matrixes of the theta alpha ratio index (a) and the gamma power (b) with ES- scores

4. DISCUSSION

The mechanical road traffic noise influenced both the positive and negative components of the emotional saliency. More mechanical caused more negative feelings and less positive feelings. More objective descriptors were linked to other negative aspects of the emotional feelings. Natural features are inversely correlated to ES- contrary to smooth and rhythmic. The results confirmed the effectiveness of introducing natural sounds for noise masking (30). Some controversial evidence already indicates the complicated effects of the temporal characteristics of water sounds for noise masking (4,31). Our results suggested that the design of spatial and temporal characteristics of water sounds needs more consideration for improving positive effects.

The overall effects of the alpha band power revealed the positive effects of spatial settings react on ES+ scores, suggesting the more relaxed and positive state of the brain induced by water sounds, especially with spatial settings (TSW and FMW conditions). The difference between left-right inter-region and right intra-region alpha connectivity refers to the activation level of the default mode network (DMN), which is a network of interacting brain regions that are active in a resting state other than performing a task accompanied by more inter-regions activity and less intra-region connections in brain activities (32) could relate to the ES+ scores differently no matter of the water sound conditions or only traffic noise.

The theta alpha ratio index, often used as task load of mental state (33), was surprisingly negatively related to negative feelings observed in the right region (the partial correlation results showed the index in the frontal region had a positive relationship with ES- after control the index in the right region, r=0.237, p=0.047). Some evidence suggested that the theta/alpha synchronization in the temporal cortex could reflect successful auditory memory encoding (34,35). Combined with the work from Raufi and Longowhich (36), the results suggested that more investigation is needed to clarify the relationship between different regions of the alpha theta ratio index in different contexts and environment settings. The gamma power strongly reflected the negative components of emotional saliency in central and posterior regions of the brain. The central gamma power was positively related to ES-. Meanwhile, the posterior region was inversely related to the ES- scores. Some researchers have demonstrated that the posterior gamma power is linked with visual information and memory encoding, and the central gamma power reflects spatial attention and emotional processing (37,38). The gamma power of different regions could bring more insights into brain activities regarding spatial attention and memory in a noisy environment, and more multisensory investigation is needed.

5. CONCLUSIONS

Traffic noise is considered a health threat for citizens in urban cities. Landscape designers and engineers are developing more effective strategies of noise mitigation. Through an immersive spatial audio system, three different spatial settings of water-sound sequences were added into the virtual acoustical environment to investigate the role of the spatialization of water-sound sequences on traffic noise masking. The neural responses and subjective self-reported evaluations collected during the auditory experiment showed preliminary correlations between the self-report evaluation of the objective features of the sound environment, the perceived emotions and EEG indicators, including spectral power, cognitive indexes and brain network connectivity.

The more positive effects on noise masking induced by the spatial setting of water sound sequences had been illustrated by the collinear relationship between the objective descriptors, the brain networks activities in the alpha band and positive emotional saliency scores. Moreover, the spectral power of the gamma band and the theta alpha ratios used as the cognitive load index had shown relationship with the negative emotional saliency that need further and deeper investigations.

The results also suggest investigating the existing differences existing from the explicit and implicit individual responses to noise.

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