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Effects of the Spatialisation of Water-Sounds Sequences on the Perception of Traffic Noise

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Abstract In the last decades, different researchers have shown the positive effects of informational masking (IM) on mitigating traffic noise perception and improving the local soundscape in urban parks. Most of these studies have tested various water sounds at different signal-to-noise ratios to optimise the selection and the sound levels to set the water sounds playback. However, less is known about the effects of the spatial distribution and movement of water sounds on the perception of the surrounding environment. Three different water-sounds sequences, and one control condition with only traffic noise, were created and used in an online experiment to investigate the role of spatialisation of water-sounds sequences. The sequences include a frontal fixed-position water sound, a two-position switching water sound and a four-position-randomised moving water sound. All of them were superimposed with a background traffic noise. Thirty-six subjects participated and answered an online questionnaire consisting of sets of items to describe the sound's perception and feeling. The Perceived Restorativeness Scale (PRS-11) was also administered. The results have shown that introducing water-sounds sequences improves some components of the restorative qualities (Fascination and Being-Away). Moreover, different spatialisation settings of water sounds proved to modify people's perception and feelings in different aspects, including attractiveness, smoothness, mechanicalness, stimulation, and nervousness.

Keywords: spatial variation; water sound; traffic noise; informational masking.

1. Introduction

Traffic noise represents one of the most important public issues of modern cities due to the rapid development of transportation. While conventional noise reduction methods focus on constraining noise emissions and transmission by insulation and absorption techniques, the soundscape approach develops alternative solutions by optimising the relationship between the sonic environment and human perception [1]. Numerous studies have demonstrated the viability of introducing natural sounds (e.g. water sound, bird songs) into noisy urban environments for mitigating noise perception [2-3]. Jeon and his colleagues found that stream and wave sounds were preferred to sounds generated by birds, wind, and the church's bell when masking traffic noise through field surveys and laboratory experiments. They also found that the level of the water sounds should be similar to or not less than 3 dB below the level of the urban noises [4].

The masking effect of water sounds for traffic noise can be attributed to auditory masking, both in the form of 'energetic' and 'informational' masking. Jeon et al. illustrated that water sounds with relatively greater energy in low-frequency ranges were effective for masking traffic noise [5]. The informational masking could be account for the auditory similarity between the water sounds and traffic noises [6]. Many studies have tested water sounds at different signal-to-noise ratios to optimise the soundscape quality and the desired sound levels to mask traffic noise [3, 7, 8]. Jeon and his colleagues found that the psychoacoustic metric sharpness had a strong positive correlation coefficient with the preference scores of water sounds combined with traffic noise [7]. Water sound preference is also supported by the change state hypothesis [9], which suggests that the automatic processing of temporally varying sounds activates the same process that are required in maintaining order information in short-term memory. Evidence showed water sounds can attract bottom-up attention and improve performance of short-term memory task [10].

However, researches about the effect of the spatial distribution of water sound are very limited. Several studies have shown the influence of spatial configuration on perceived sound quality and emotional feelings. Lepa and his colleagues studied the emotional impacts of spatialisation type (stereo headphones/stereo loudspeakers/live concert simulation) and spatial quality expectations (yes/no). They found significant spatialisation types on perceived affective expressivity of music and spatial audio quality [11]. Deng, with his colleagues, studied the auditory spatial perception of the soundscape environment based on 21 native binaural-recorded soundscape samples and a set of auditory experiments. The results showed that the more noisiness the audience perceived, the worse spatial awareness they received [12]. Hong and others explored the effects of spatial separations between target noise and water sound on Perceived Loudness of target Noise (PLN) and Overall Soundscape Quality (OSQ) through laboratory experiments. The results indicated that the effect of the spatial separation between the traffic noise and water sound was significant in both PLN and OSQ. Specifically, the PLN increase at 135° separation was equivalent to an estimated target noise level increment of ~1–2 dB. And the OSQ decrease, at 135° and 180° separations, was equivalent to an estimated target noise level increase of ~2–5 dB [13].

In real-life situations, it is hard to take full advantage of human perception in noisy environments because of the spatial-temporal variation of the environment and its mutual effect on human actions. Also, practical measures for noise abatement may be limited in urban parks, especially in those pocket parks. Some researchers and designers have recently devoted to introducing sound installations into urban parks as practical measures for noise control and soundscape improvement. Cerwén used a small arbour with sound screen to explore how urban soundscapes can be altered through outdoor space design. The findings revealed that the arbour improved the soundscape, which could be further enhanced by adding forest sounds through loudspeakers [14]. Masullo and his colleagues 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 effects with water's sounds at levels 3 dB lower than the road-traffic background noise. Moreover, installations with water features improve their restorativeness on escaping and fascination components [15]. 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 significantly positive effects on restorativeness's Fascination and Being-Away components [16,17]. Fraisse with other researchers designed and evaluated a sound installation in a public square in Montreal exposed to construction noise. The results showed that sound improved the soundscape of the public square, particularly when the public square was exposed to construction noise [18].

This paper used water-sound sequences with different spatialisation settings to investigate their masking effect on road traffic noise perception. This was done through semantic reports that give us more insight into the relationship between the spatialisation of water sound and the informational masking of noise. The results will also provide us with workable thoughts of urban design for noise mitigation.

2. Methods

2.1. Experimental design

A within-subjects experimental design was used. The independent variable was the spatialisation of the water sounds. Four levels of spatialisation 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 empty water sound, all of them combined the *Road Traffic Noise* (RTN) on frontal position as background. The two-position pair of TSW included four different settings: frontal-left pair, frontal-right pair, back-left pair, back-right pair. Dependent variables are subjective responses obtained by questionnaires during each condition. The study hypothesises that a structural, spatial representation of water sounds in a noisy environment would produce more positive subjective feelings than fixed or co-located water sound, leading to the decreasement of mental stress and increasement restorative qualities.

2.2. Sound materials

The sound sources included 1-minute traffic noise recorded by Zoom H6 Hand-Recorder device with a Soundfield SPS200 microphone (LAeq: 65 dB(A)) in Villa Comunale in Naples in Italy as background sound (BGs), and 5 seconds water stream sound recorded by Zoom H6 Hand-Recorder device with Rode NTG – 2 microphone (LAeq: 62 dB(A)) in Sant'Agata De Goti in Caserta in Italy. 1-minute long mono soundtracks A and B were created for spatial sound reproduction using repeated 5 seconds water sound with 2 seconds fade-in and fade-out concatenation segments and split intersectingly in a sequential order with 2 seconds overlap.

The soundtracks were played back within the SENS i-Lab of the Department of Architecture and Industrial Design of the Università degli Studi della Campania "Luigi Vanvitelli" through an Astro Spatial Audio system (ASA) (25 Adorn A55 Martin Audio; 2 Sx110 Martin Audio), and rendered by SARA II Premium

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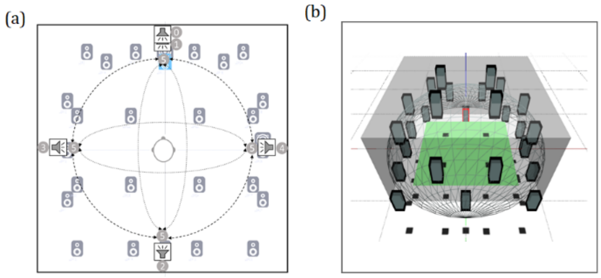
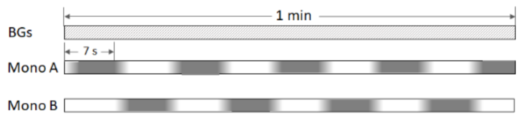
Rendering Engine. The experimenter controlled these sound sequences via browser-based GUI and captured them by binaural recordings used as sound materials for the online test. RTN was set at the frontal position of subjects, while the Dummy-Head was positioned at the centre of the test room of the SENS i-Lab for binaural recording. FPW also co-located with traffic noise sound. For TSW settings, four two-position pairs were defined as frontal-right pair, right-back pair, back-left pair, and left-front pair. The distance between each position soundtrack up to subject was the same as RTN. For FMW, pseudo-random routine of the water sound selected from four-position (frontal/back/left/right) was defined at the ASA application (see Fig. 1).

(a) (b)



(c)



(d)

	FPW	TSW	FMW	RTN
Mono A	1	1/2/3/4	5	off
Mono B	off	4/3/1/2	off	off
BGs	0	0	0	0

Figure 1. Spatial configuration of sound sequences: a) 2d illustration of spatial position for sound with loudspeakers, b) 3d illustration of physical loudspeakers, c) three sound sequences, d) four sound conditions using different sequences and positions.

2.3. Procedure

The sound materials of the four conditions were recorded in the test room with a binaural recording device and calibrated at the same sound equivalent level (about 57 dB(A)). The questionnaire included five-sound sequences from four conditions, one for each condition except for TSW, in which two different position-pair water sounds were assigned randomly. The assessment of each sound sequence consisted of three parts across three pages on the online website, including the soundscape perception, subjective evaluations based on previous works [18-19] and the Perceived Restorativeness Scale (PRS-11) separately. The order of five sound sequences was randomised. The online test was published on the website (http://braincoder.io/spatial_sound/en/)[20] with constrained design for appearance controlment. Subjects were invited to finish the test online by email. Thirty-six subjects (male:21; female:15; average age: 26 yrs) were equally enrolled from Chinese and Italian universities. Subjects were also asked for using headphones in a quiet environment and keeping head steady during the test. A male speech voice recording has been used at the beginning of the test to allow the subjects to calibrate the playback level of the sound stimuli, asking them to adjust the system volume until the male voice sounded loud as a normal speech of a talker at about 1m in a quiet room. After the volume setting, subjects were asked not to change the system volume. The audio player's settings inside the website were kept constant. The online test last 15-20 minutes. All data collected was safely stored on a personal database. No private information of those who participated in the online questionnaire was collected.

3. Results

3.1. Perceived Restorativeness Scale (PRS-11)

The Perceived Restorativeness Scale (PRS-11) items [21] based on Kaplan and Kaplan's Attention Restoration Theory was categorised into four dimensions: being away; fascination; coherence and scope [22].

In the Being Away factor of PRS-11 scores, repeated measures ANOVA results showed the difference between four conditions was significant ($F(3,105) = 2.91$, $p = 0.038$, $\eta_p^2 = 0.077$; see Tab. 1). The results of post hoc analysis (with Tukey correction) illustrated that the FMW was significantly better than RTN ($df = 105$, $t = 2.682$, $p_{tukey} = 0.042$). However, other conditions were not significantly different from traffic noise (see Fig. 2). In the Fascination factor of PRS-11 scores, the ANOVA results indicated the differences between four condition were significant ($F(3,105) = 7.29$, $p < 0.001$, $\eta_p^2 = 0.172$) (see Tab. 1). The results of post hoc analysis illustrated the scores of TSW, FPW and FMW were all significantly higher than RTN ($df = 105$, $t = 4.538$, $p_{tukey} < 0.001$; $df = 105$, $t = 3.167$, $p_{tukey} = 0.011$; $df = 105$, $t = 2.937$, $p_{tukey} = 0.021$). However, the differences among those three conditions were not significant (see Fig. 2).

No significant results between four spatialisation conditions were observed for the remaining dimensions of PRS-11 (see Fig. 2).

Table 1. Mean values (standard error) and effect sizes of four conditions in PRS-11 dimensions.

Variables	Spatial sounds				*df*	*F*	*p*	η_p^2	Significance
	TSW	FPW	FMW	RTN					
Being away	2.74(0.343)	2.35(0.343)	2.87(0.343)	1.87(0.343)	3	2.91	0.038	0.077	*
Coherence	3.54(0.347)	3.75(0.347)	3.38(0.347)	3.43 (0.347)	3	0.574	0.633	0.016	
Fascination	3.31(0.275)	2.87(0.275)	2.80(0.275)	1.87(0.275)	3	7.29	<.001	0.172	***
Scope	4.03(0.377)	4.17(0.377)	4.19(0.377)	3.89(0.377)	3	0.288	0.834	0.008	

Note: η_p^2 = partial eta squared; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; the same below.

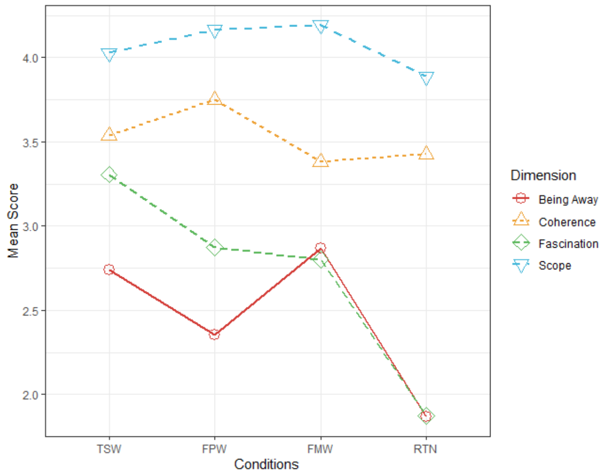


Figure 2. PRS-11 mean scores of four conditions in four dimensions.

3.2. Sound evaluation scale

The results related to the feature judgements of each sounds included *naturalness*, *mechanicalness*, *smoothness*, *rhythmicalness*, *spaciousness*, and *familiarity* were analysed.

From the one-way ANOVA analysis, the *naturalness* of each sound condition was significantly different ($F(3,105) = 10.2$, $p < 0.001$, $\eta_p^2 = 0.226$) (see Tab. 2). The results of post hoc analysis showed TSW, FMW and FMW were all significantly better than RTN ($df = 105$, $t = 4.807$, $p_{\text{tukey}} < 0.001$; $df = 105$, $t = 4.760$, $p_{\text{tukey}} < 0.001$; $df = 105$, $t = 2.885$, $p_{tukey} = 0.024$). Significant differences of the *mechanicalness* of each sound were observed ($F(3,105) = 7.09$, $p < 0.001$, $\eta_p^2 = 0.168$; see Tab. 2). The results of post hoc analysis illustrated FPW and RTN were all significantly higher than TSW ($df = 105$, $t = 3.268$, $p_{\text{tukey}} = 0.008$; $df = 105$, $t = 4.445$, $p_{\text{tukey}} < 0.001$). But the difference between TSW and FMW was not significant ($df = 105$, $t = 2.385$, $p_{\text{tukey}} = 0.086$). The *smoothness* among each sound was significantly different ($F(3,105) = 2.89$, $p = 0.039$, $\eta_p^2 = 0.076$). The results of post hoc analysis illustrated TSW was significantly higher than RTN ($df = 105$, $t = 2.907$, $p_{\text{tukey}} = 0.023$). The differences of other descriptors between the four conditions were all insignificant (see Fig. 3a).

Table 2. Mean values (standard error) and effect sizes of four conditions in feature judgements.

Variables	Spatial sounds				*df*	*F*	*p*	η_p^2	Significance
	TSW	FPW	FMW	RTN					
Naturalness	3.65(0.276)	3.64(0.276)	3.08(0.276)	2.23(0.276)	3	10.2	<.001	0.226	***
Mechanicalness	2.69 (0.280)	3.61(0.280)	3.36(0.280)	3.94 (0.280)	3	7.09	<.001	0.168	***
Smoothness	2.96 (0.231)	2.67(0.231)	2.56(0.231)	2.22(0.231)	3	2.89	0.039	0.076	*
Rhythmicalness	2.63(0.217)	2.80(0.217)	2.61(0.217)	2.17(0.217)	3	2.58	0.058	0.069	
Spaciousness	3.78(0.269)	3.67(0.269)	3.72(0.269)	3.50(0.269)	3	0.382	0.767	0.011	
Familiarity	3.76(0.292)	3.81(0.292)	3.58(0.292)	4.19(0.292)	3	1.78	0.155	0.048	

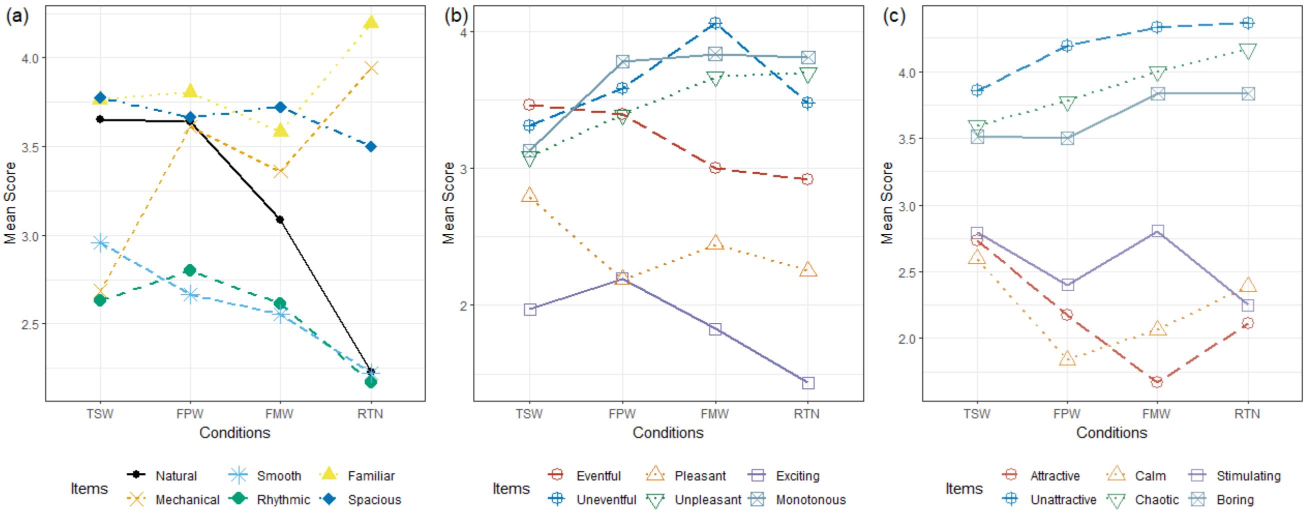


Figure 3. Mean score of sound evaluation scales: a) items related to feature judgements, b) c) items related to soundscape indicators.

The ANOVA on the soundscape indicators included *eventfulness/uneventfulness* and *pleasantness/unpleasantness* within Axelsson and Cain's circumplex model showed no significant differences among the four sounds [23,24]. But the *calmness* and *excitement* factors in the model illustrated significant differences among those conditions (Calmness: $F(3,105) = 3.80$, $p = 0.012$, $\eta_p^2 = 0.098$; Excitement: $F(3,105) = 6.01$, $p < 0.001$, $\eta_p^2 = 0.146$; see Tab. 3). The results of post hoc analysis illustrated the *calmness* ratings of TSW was significantly better than FPW ($df = 105$, $t = 3.103$, $p_{tukey} = 0.013$; see Fig. 3c). And the *excitement* ratings of TSW and FPW were all significantly better than RTN ($df = 105$, $t = 2.910$, $p_{tukey} = 0.023$; $df = 105$, $t = 4.122$, $p_{tukey} < 0.001$; see Fig. 3b). However, the difference between FMW and RTN was not significant ($df = 105$, $t = 2.141$, $p_{tukey} = 0.147$; see Fig. 3c). Besides, the *attractiveness* among those sounds was significantly different ($F(3,105) = 5.53$, $p = 0.001$, $\eta_p^2 = 0.136$; see Tab. 3). The results of post hoc analysis illustrated TSW was significantly better than FMW ($df = 105$, $t = 4.055$, $p_{tukey} < 0.001$; see Fig. 3c). And the differences in the *stimulation* of each sound were also significant ($F(3,105) = 2.72$, $p = 0.048$, $\eta_p^2 = 0.072$; see Tab. 3). However, the results of post hoc analysis illustrated no significant difference between all conditions.

Table 3. Mean values (standard error) and effect sizes of four conditions in soundscape indicators.

Variables	Spatial sounds				*df*	*F*	*p*	η_p^2	Significance
	TSW	FPW	FMW	RTN					
Eventfulness	3.46(0.242)	3.39(0.242)	3.00(0.242)	2.92(0.242)	3	2.06	0.110	0.056	
Uneventfulness	3.31(0.292)	3.58(0.292)	4.06(0.292)	3.47(0.292)	3	1.96	0.124	0.053	
Pleasantness	2.79(0.206)	2.19(0.206)	2.44(0.206)	2.25(0.206)	3	2.51	0.063	0.067	
Unpleasantness	3.08(0.313)	3.39(0.313)	3.67(0.313)	3.69(0.313)	3	1.67	0.178	0.046	
Excitement	1.97(0.158)	2.19(0.158)	1.83(0.158)	1.43(0.158)	3	6.01	<.001	0.146	***
Monotonousness	3.13(0.278)	3.78(0.278)	3.83(0.278)	3.81(0.278)	3	2.04	0.113	0.055	
Calmness	2.60(0.200)	1.84(0.200)	2.06(0.200)	2.39(0.200)	3	3.80	0.012	0.098	*
Chaoticness	3.60(0.288)	3.78(0.288)	4.00(0.288)	4.17(0.288)	3	2.24	0.232	0.040	
Stimulation	2.79(0.219)	2.40(0.219)	2.81(0.219)	2.25(0.219)	3	2.72	0.048	0.072	*
Boredom	3.51(0.319)	3.50(0.319)	3.83(0.319)	3.83(0.319)	3	0.785	0.505	0.022	
Attractiveness	2.74(0.209)	2.17(0.209)	1.67(0.209)	2.11(0.209)	3	5.53	0.001	0.136	**
Unattractiveness	3.86(0.310)	4.19(0.310)	4.33(0.310)	4.36(0.310)	3	0.842	0.474	0.024	

3.3. Emotional feelings scale

The nervousness ratings were the only significant results among the six dimensions of the emotional feelings scale (calm/energetic/happy/nervous/sad/weak) for the four sound conditions ($F(3,105) = 4.87$, $p = 0.003$, $\eta_p^2 = 0.122$; see Tab. 4). The results of post hoc analysis illustrated TSW was significantly lower than RTN ($df = 105$, $t = -3.793$, $p_{tukey} < 0.001$; see Fig. 4). But the differences between the rest two conditions and traffic noise were not significant.

Table 4. Mean values (standard error) and effect sizes of four conditions in emotional responses.

Variables	Spatial sounds				*df*	*F*	*p*	η_p^2	Significance
	TSW	FPW	FMW	RTN					
Happy	2.24(0.212)	2.06(0.212)	2.11(0.212)	1.71(0.212)	3	2.19	0.093	0.059	
Sad	1.99(0.216)	2.08(0.216)	1.97(0.216)	2.17(0.216)	3	0.493	0.688	0.014	
Energetic	2.16(0.194)	2.11(0.194)	2.17(0.194)	2.03(0.194)	3	0.217	0.885	0.006	
Weak	2.42(0.237)	2.31(0.237)	2.36(0.237)	2.31(0.237)	3	0.175	0.913	0.005	
Calm	2.71(0.234)	2.56(0.234)	2.56(0.234)	2.19(0.234)	3	1.53	0.212	0.042	
Nervous	2.30(0.261)	2.86(0.261)	2.81(0.261)	3.22(0.261)	3	4.87	0.003	0.122	**

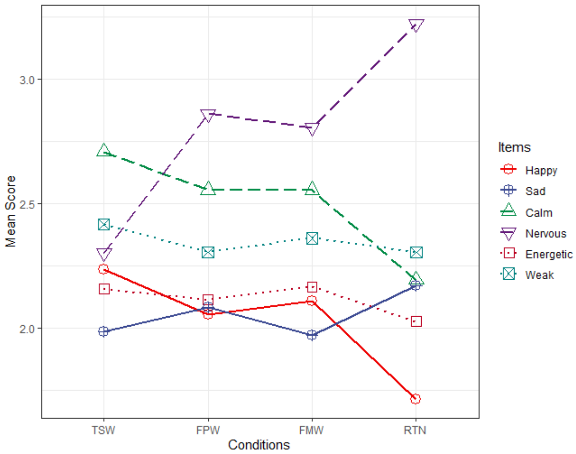


Figure 4. Mean Scores of Four Conditions in Emotion Feelings.

4. Discussion

4.1. Water sound and restorative qualities

The introduction of water sound increased restorative qualities in being-away and fascination dimensions. However, it seemed different properties of the water sound acted on different dimensions. The result that the four-position pseudo-random moving water sound was better than other water sounds in being-away dimension indicated that more spatial varieties could improve this restorative quality in sonic environment. Moreover, all three water sounds improved the Fascination of the soundscape, suggesting many benefits of the inherent nature of water sound to this restorative quality. No effect on the coherence and scope dimensions could cause by lacking strong space cues like visual impressions in our study, which is also indicated by the study of Hong et al. [13]. The visibility of water sound could enhance acoustic qualities of the place [16, 17], which provides us some hints to our next step of the research topic.

4.2. Spatial variation and perceived aspects

All water sounds increased the naturalness of the soundscape, and the two position switching water sound, which provided a rich and stable space representation, created more smooth and less mechanical effects. However, there were no main differences of the four conditions related to *eventfulness/uneventfulness* and *pleasantness/unpleasantness* . The reason could be related to the road traffic noise which mixed with few bird songs, human voices and other sounds. The scale of annoyance indicated the road traffic was not so annoying ($F(3,105) = 0.244$, $p = 0.865$, $\eta_p^2 = 0.007$) across all conditions. The limitations of the online approach could also be another reason. Lacking full control of the sonic environment and of the visual context of the experiment may have caused less concentrated and sensitive responses from subjects' reports. Therefore, experimental methods across multiple modalities are helpful for further research.

However, some aspects of perception and feelings were changed by different spatial variations of water sounds. The separated positions of water sound and traffic noise did not influence the perceived calmness of the soundscape in contrary to co-location of water sound and traffic noise. Furthermore, the stable spatial representations of water sounds included the frontal-fixed position water sound and the two-position switching water sound, both improved the excitement content of the soundscape. All those results indicated that the spatial variation of sounds influenced the perceived qualities of soundscape from different aspects. Moreover, the nervous feeling caused by the two-position water sound was the least, directly suggesting its positive effect on mental stress.

5. Conclusions

The main purpose of this study was to investigate the effect of different spatial variations of water-sounds sequences on masking traffic noise. Four water-sounds sequences were accomplished by binaural recordings produced by a spatial sound system and evaluated by thirty-six subjects through online questionnaires. The results showed that water sounds with two separated spatial settings can help to decrease mental stress and increase multiple positive feelings. And it also deserved to mention that the spatial distribution affected the masking effect of water sound on the perception of traffic noise from different aspects. More studies across multiple modalities are needed for further clarifying the complex relationship between temporal-spatial variations of sound sources and the perception of traffic noise. And it will certainly help landscape designers and managers to develop more various approaches for noise abatement and environment protection.

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