



Article Effect of Road and Railway Sound on Psychological and Physiological Responses in an Office Environment

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Abstract: The present study aims to explore the psychophysiological impact of different traffic sounds in office spaces. In this experiment, 30 subjects were recruited and exposed to different traffic sounds in a virtual reality (VR) office scene. The road traffic sound and three railway sounds (conventional train, high-speed train, and tram) with three sound levels (45, 55, and 65 dB) were used as the acoustic stimuli. Physiological responses, electrodermal activity (EDA) and heart rate (HR) were monitored throughout the experiment. Psychological evaluations under each acoustic stimulus were also measured using scales within the VR system. The results showed that both the psychological and the physiological responses were significantly affected by the traffic sounds. As for psychological responses, considerable adverse effects of traffic sounds were observed, which constantly increased with the increase in the sound level. The peak sound level was found to have a better performance than the equivalent sound level in the assessment of the psychological impact of traffic sounds. As for the physiological responses, significant effects of both the acoustic factors (sound type and sound level) and the non-acoustic factors (gender and exposure time) were observed. The relationship between sound level and physiological parameters varied among different sound groups. The variation in sound level hardly affected the participants' HR and EDA when exposed to the conventional train and tram sounds. In contrast, HR and EDA were significantly affected by the levels of road traffic sound and high-speed train sound. Through a correlation analysis, a relatively weak correlation between the psychological evaluations and HR was found.

Keywords: road traffic sound; conventional train sound; high-speed train sound; tram sound; electrodermal activity; heart rate; acoustic comfort; noise annoyance

1. Introduction

Recent surveys suggest that office employees are the most dissatisfied with the acoustic environment when various factors of the physical indoor environment are enquired [1]. Noise was found to be influential not only on the perception of the overall environment, but also on the working performance in offices [2,3]. Landström revealed the relationship between low-frequency noises and fatigue in the working environment [4]. Focusing on the open-planned offices, the most annoying sounds were found to be noises from outside, ventilation systems, office equipment, and keyboard typing [5]. As for the home working space, the sounds from other people at home, neighbors, construction, and traffic were reported as the most negatively evaluated sounds [6]. As reported, traffic sound is a major source of environmental sound pollution [7], and 81% of the workers around major streets are annoyed by traffic sounds [8]. With rapid urban growth all over the world [9,10] and increasing demand for better transportation systems, a simultaneous increase in traffic sound exposure and the associated impact on residents can be anticipated. Therefore, it is important to perform a comprehensive investigation on the adverse effect of traffic sounds on the agenda of sound policies and urban development.

Exposure to traffic sounds has been proven to be associated with an increased risk of negative health outcomes both physiologically and psychologically [11–13]. Psychological



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). attributes, such as noise annoyance, are the most widely used measures for evaluating the impact of traffic sounds [14–17]. It was found that traffic-related noise annoyance had a considerable impact on health-related quality of life [18]. With the increase in the sound level, exponential growth in the percentage of highly annoyed people was found by large-scale surveys, namely, the dose-response curve [17]. In the past several decades, the dose-response curve has been used as direct scientific evidence for most sound policies and regulations. In addition to noise annoyance, traffic sounds were found to have a significant influence on how people perceive the overall urban soundscape [19,20]. Considering the diversity of the urban context, it has been suggested that the perception of the acoustic environment was multidimensional [21,22]. A two-dimensional scale is widely used for evaluating the psychological response to the acoustic environment, including the eventfulness (arousal) and pleasantness (pleasant) [23-25]. In addition, acoustic comfort is also widely used as a measure of the quality of the overall sound environment [26-28]. Focusing on the indoor acoustic environment, another two-dimensional scale (comfortcontent) was suggested to evaluate the soundscape quality [29]. Through a virtual reality experiment, this model was proved to be efficient for evaluating the work-related quality in open-plan offices [2]. In almost all relevant studies, the traffic sounds were found to have an adverse effect on the perception of the acoustic environment, which increased with the sound level [30].

In addition to psychological responses, the physiological responses to traffic sounds were also investigated to reveal the potential effect on health [31–33]. Significant impacts of traffic sound on physiological responses have been reported in the literature. In laboratory experiments, Vera et al. found that the exposure to high-intensity traffic sound with negative self-statements produced a significant electromyography (EMG) increase [32]. Significant increases in electroencephalographic (EEG) indices and HR with the increase in sound level were reported by Basner et al. [34]. Similar results were also reported by Raggam et al. [35]; the presence of traffic sounds led to an increase in heart rate (HR), although the respiratory rate (RR) was unaffected. In a recent field study, strong associations between blood pressure and traffic sounds were found [36]. Laboratory experiments are more commonly used for investigating the physiological effect of traffic sounds and to control non-experimental factors. Under audio-video stimuli [37], higher HR, heart rate variability (HRV), RR, amplitude of the R wave, and SCL were found when close to the traffic sound source. A higher skin conductance level (SCL) was observed when the traffic sound was mixed with the natural sound [38]. In the field of soundscape research, similar results could be found when the traffic sounds were compared with other urban sounds [25,39–41]. The relationship between physiological responses and exposure time has revealed that the introduction of sound stimuli led to an immediate change in physiological parameters in the first 30 to 60 s, including EDA and HR. With the increase in exposure time, participants gradually adapted to the sound stimuli and the physiological parameters gradually returned to the baseline levels [38,41,42]. In most previous studies, it was found that the baseline level of physiological parameters was highly dependent on personal characteristics [38,41]. Therefore, the change in physiological parameters is commonly used to reveal the effect of sound stimuli on people.

There are only very few studies that have investigated the effect of traffic sounds in office spaces, and which have mainly focused on the psychological attributes. Through a questionnaire survey, traffic sound was identified as the cause of annoyance, activity disturbance, and headaches [43]. A positive correlation between the sound level and the percentage of annoyed people was identified [8]. In addition, annoyance caused by the traffic sound was found to be influential on the psychological state, including anxiety [44], fatigue, and tension [45]. As for the overall acoustic environment, the traffic sound was also found to harm the overall acoustic comfort in office buildings [46]. However, to the best of the authors' knowledge, research on the physiological responses to traffic sounds in office spaces is not detailed.

Meanwhile, most of the existing literature has mainly focused on the effect of sound level variation of road traffic sound [37], whereas very few studies have compared the responses to different traffic sounds. However, there are considerable differences between different traffic sounds on not only the physical characteristics, but also on the impact on people [30,47]. In very few studies which examined the psychophysiological responses under different sound sources [36,48], simultaneous consideration of the sound type and the sound level was not detailed, to the authors' knowledge. However, for effective sound control treatment, it is important to determine the interaction effect of the sound type and the sound level on people.

Our analysis indicated that the following questions on the topic of psychophysiological responses under the impact of traffic noises in office spaces still need to be addressed:

- (a) What are the psychophysiological effects of different traffic sounds in office spaces?;
- (b) Do the increases in sound levels interfere with the psychophysiological responses to traffic sounds?;
- (c) Do the other factors (gender and exposure time) interfere with the psychophysiological responses to traffic sounds?;
- (d) Are there correlations between psychological responses and physiological responses under the impact of traffic sounds?

Therefore, in the present study, we conducted laboratory experiments to measure the psychophysiological responses of 30 respondents under different traffic sound configurations. The interaction effects of sound type and sound level on the psychological and physiological responses were examined. This paper was organized as follows. The experiment implementations are shown in Section 2. Section 3 shows the results that reveal the influential factors of psychophysiological parameters when exposed to traffic sounds. In addition, the correlations between psychological responses and physiological responses are shown in Section 3. Sections 4 and 5 summarize the discussion on related issues and the main findings of this study.

2. Methodology

2.1. Participants

There were 30 subjects ranging in age from 19 to 26 years participating in the experiment (15 male and 15 female). All of the participants reported having normal hearing and corrected vision. None of them was taking prescription medication. All of the participants were informed about the aim and protocol of the experiment, and they voluntarily participated in the study.

2.2. Experiment Stimuli

The experiment was conducted in an office-like experimental chamber, where the physical environment was controlled (temperature = $21 \sim 23$ °C; background sound level < 25 dBA). To provide a complete and realistic presentation of an office and avoid other distractions in the lab, immersive virtual reality (VR) technology was employed in this study. An omnidirectional picture of an actual open-planned office was taken and played in the VR head-mounted display (HTC VIVE Pro EYE; Resolution: 2880×1600 ; Refresh rate: 90 Hz) during the experiments, as shown in Figure 1.

In this study, four traffic sounds (including road traffic, conventional train, highspeed train, and tram sounds) were used to generate the sound stimuli. The four traffic sounds were selected for the following reasons: (1) they are very common traffic sounds in urban areas and are frequently considered in relevant studies [49–52]; and (2) they are reported to have different influences on subjective evaluation and could have potential differences on psychophysiological effects [36]. All the sound stimuli were extracted from field recordings collected in Beijing, China. The sound recordings were all collected in quiet areas to avoid accidental sounds. A sound meter (6228+, Aihua, Hangzhou, China) was used to conduct sound recordings and measurements under the same format (48 kHz, single-channel, 16 bits). Then, 2 min clips were extracted from the field recordings as the experimental stimuli. Specifically, the road traffic sound was recorded near a city highway. A continuous 2 min clip was then extracted. However, the railway sounds were discontinuous, with the duration time varying from 15 s to 45 s, as shown in Figure 2. Moreover, the time period between two trains was not the same. For standardization, a 1 min clip with one train passing by was extracted and then repeated to produce a 2 min experimental stimulus. Therefore, in each railway sound stimulus, there were two trains passing by. The spectrograms of four traffic sound stimuli are shown in Figure 2. It could be found that there were both spectral and temporal differences between different traffic sounds. In general, the spectral characteristics of all traffic sounds were similar, whereas the railway sounds contained more high-frequency components. Moreover, the temporal differences were much more significant between road traffic sounds and railway sounds. The road traffic sound was mainly continuous and steady, whereas the railway sounds were intermittent and fluctuating. Due to the differences in speed and train length, the tram sounds exhibit a minimum duration of approximately 15 s, whereas the duration of the conventional train sound was approximately 45 s.



Figure 1. The panoramic view of an open-plan office.

The sound level was another considered experimental factor in the experiment. According to sound regulations and the existing literature [11,36], the sounds (A-weighted equivalent sound level) were set at 3 levels in this study: 45, 55, and 65 dBA. The sound stimuli were replayed through reference class Sennheiser 650 HD headphones to ensure the spectral accuracy of the emitted signal with respect to the real sound. The equivalent sound level of the single-channel signal was measured by a class 1 sound level meter (6228+, Aihua, Hangzhou, China) placed 1 cm away from the headphones. Then, the sound levels of the stimuli were calibrated to the standard sound levels (45, 55, and 65 dB) in Cooledit software. Finally, the single-channel signals were copied to produce the dual-channel stimuli.

In addition, silence was used as the control stimulus to conduct baseline measurements. The duration of silence was also set as 2 min. Altogether, 13 acoustic stimuli were used in the study. During the experiment, sound signals of the acoustic stimuli were delivered by a computer through the headphones.



Figure 2. Spectrogram of the experiment stimuli, including road traffic sound (R), conventional train sound (C), high-speed train sound (H), and tram sound (T).

2.3. Measures

To measure the physiological responses to traffic sounds, two simple measures were applied: electrodermal activity (EDA) and heart rate (HR). These two indices are widely used to assess the physiological response to sound stimuli and are suggested as sensitive indicators for evaluating the impact of sounds [39,41,42,53]. The EDA was measured using two electrodes (HKR-11, range: 100 to 2500 k Ω ; accuracy: 2.5 k Ω ; sample frequency: 50 Hz) attached to the subject's index and middle fingers of the non-dominant hand. The HR was measured by a photoplethysmography (PPG) sensor (HKG-07, range: 30 to 250 bpm; accuracy: 1 bpm; sample frequency: 16 Hz) attached to the ring finger [53]. The study protocol enabled us to record EDA and ECG simultaneously while the participants were exposed to the experimental stimuli.

As for the psychological attributes, a questionnaire with four aspects was used to assess the psychological effect of traffic sounds in this study. The questionnaire was implemented in the VR system, which appeared after each sound stimulus to avoid influences caused by removing VR equipment. The first used attribute was noise annoyance (AN), which is widely used to evaluate the impact of traffic sounds. A five-point verbal ICBEN (International Commission on Biological Effects of Noise) scale was used with the verbal marks: (1) "not annoyed at all"; (2) "slightly annoyed"; (3) "moderately annoyed"; (4) "very annoyed"; and (5) "extremely annoyed" [54]. The Self-Assessment Manikin (SAM) was used to measure the evoking state associated with experiencing sound stimuli [55,56]. The SAM is commonly applied using graphic scales and cartoon characters to explain the meanings of the scales [41,56]. A modified nine-point numerical scale has been proposed to rate the psychological state when exposed to sound stimuli [25]. Due to size limitations of the questionnaire, nine-point numerical scales were used in this study for the evaluation of arousal and pleasantness evoked by the acoustic stimuli with descriptions: (1) no arousal at all/completely unpleasant; (9) complete arousal/completely pleasant) [25]. In addition, acoustic comfort (AC) was used as an assessment of the overall acoustic environment. Similar to the annoyance evaluation, a five-point verbal scale suggested by Yang and Kang was used with the verbal marks: (1) "very uncomfortable"; (2) "uncomfortable"; (3) "neither

comfortable nor comfortable"; (4) "comfortable"; and (5) "very comfortable" [26]. During the experiment, the experimental operator also verbally instructed the participants before the measurements. Instructions used for evaluating acoustic quality in the laboratory study were adopted and used [57]:

"Begin by listening through the 12 traffic sounds presented in the headphone, and build your opinion about their character. Thereafter you measure the traffic sounds with the aid of four attribute scales that appears in front of you. The traffic sounds must be measured one at a time on all the attribute scales and in the order presented from up to down.

Your task is to judge to what extent the attributes listed in the protocol are applicable to the traffic sounds in the current office environment."

2.4. Experimental Procedure

The experiment was generally divided into two sessions: (1) preparation and adaptation; (2) formal experiment. The participants came into the laboratory and were seated in a comfortable chair 15 min before the formal experiment to avoid the impact of physical movement. In the first 10 min, the informed consent was read and signed, basic personal information was collected and the sensors for physiological measurements were attached. After putting on the VR equipment, the participants were asked to adapt to the scene for 4 min to reduce the personal differences caused by the VR environment. The scale for psychological attributes was presented inside the VR environment; therefore, practice was necessary to avoid misunderstandings. After the adaptation session, the participants were asked to rest for 1 min with their eyes closed to remove the impact caused by the practice session. As for the formal experiment, a baseline level was measured as the reference psychophysiological response to a quiet office environment. Then, the psychophysiological responses of the participants were measured when exposed to twelve traffic sound stimuli. For each experimental stimulus, there were three periods: (1) a 2 min period of sound exposure with the continuous measurement of EDA and HR; (2) a 30 s psychological response measurement in which the participants were asked to evaluate the acoustic comfort (AC), noise annoyance (AN), arousal (AR), and pleasantness (PL) with the scales displayed in the VR scene; and (3) a 1 min rest to reduce the effect of the previous stimuli and measurement process. The order of acoustic stimuli presentation was randomized and counterbalanced. A random order of experimental stimuli was generated for each participant. The average order of each stimulus was then calculated. If the average order of any stimulus was smaller than five or larger than eight (order unbalanced), the random order generation process was repeated to maintain the balance among the experimental stimuli. The experiment process is schematically shown in Figure 3. The total time for the formal experiment was approximately 45 min.

2.5. Data Analysis

In this study, all statistical analysis was performed within SPSS 20.0 software (IBM Corp., New York, NY, USA). For the psychological attributes, the measured data were directly used in the statistical analysis, where evaluation of the silent condition was used as the reference. However, it is suggested that non-acoustical characteristics, including gender and exposure time, have a considerable effect on the physiological data [41,42]. Therefore, the 2 min measured data were divided into 20 s segments to reveal the temporal variations of the physiological index. Then, the mean changes in physiological data (EDA and HR) were calculated by comparing with the baseline measurement [41,42]:

$$Index_{change} = \frac{Index_{i,j} - Index_{baseline}}{Index_{baseline}},$$
(1)

where *i* and *j* indicate the number of traffic sound type and the time serial for each acoustic stimulus, respectively.

Session 1: Preparation and adaption	Session 2: Response to experiment stimuli			
	Baseline Measurement (Silence)	Traffic Noise Stimuli		
 Environment adaptation:10 min Scene adaptation: 4 min Rest: 1 min 	 Physiological response : 2 min Perceptual evaluation : 30 s Rest : 1 min 	 Physiological response : 2 min Perceptual evaluation : 30 s Rest : 1 min 		
Adaptation experiment and VR environment Practice to evaluate the perceptual scales in VR scenes Rest to reduce the influence of preparation session	Phase 2: Silence as the baseline measurement and twelve randomly sorted traffic noise stin 2 min physiological response under experiment stimuli was extracted 1 min rest after response measurement to remove the effect of the former stimuli			

Figure 3. Schematic diagram of the experiment process.

As for the statistical method, the multivariate analysis of variance (MANOVA) was first used to reveal the effect of experimental variables on the psychophysiological response under the impact of different traffic sounds. Before the MANOVA, the normality assumptions of the measured responses for each level of independent variables were examined with the Kolmogorov–Smirnov test. Only one dataset violated the normality assumption (EDA under 55 dB tram sound: p = 0.028). In addition, it was suggested that ANOVA could still yield robust and valid results with non-normally distributed data [58]. The homogeneity of variance was verified with the Levene's test (acoustic comfort: p = 0.493; annoyance: *p* = 0.608; arousal: *p* = 0.993; pleasantness: *p* = 0.791; EDA: *p* = 0.643; HR: *p* = 0.779). Four experimental variables were considered in the MANOVA: sound level, sound type, gender, and exposure time. As for the psychological responses, the exposure time was not included because the evaluations were performed based on the overall 2 min sound stimuli. The main effects of experimental variables on psychophysiological responses were investigated. As indicated in the previous studies, the relationship between experimental variables and psychophysiological responses might depend on the sound source. Therefore, the interaction effects of sound type and other experimental factors were also included in the MANOVA, as shown in Figure 4. The pairwise comparison was then applied to further show where the differences lay. For the main effects of independent variables, the least significant difference (LSD) was used to conduct the pairwise comparison. For the significant interaction effects found in MANOVA, a nonparametric Mann–Whitney U test was used to conduct the pairwise comparison. For example, if the interaction of sound type and sound level was found to have a significant effect on EDA, pairwise comparisons were conducted between any two sound levels in each sound group to reveal how EDA varied with the sound level. In addition, a correlation analysis was applied to investigate the relationship between physiological response and psychological attributes. In all analyses, a *p*-value less than 0.05 was used as the criterion to determine significant differences.



Figure 4. A flowchart of statistical analysis used in this study.

3. Results

3.1. Effect of Traffic Sounds on Psychological Responses

Four psychological dimensions were measured in this study, with greater values indicating higher perceived acoustic comfort (AC), annoyance (AN), arousal (AR), and pleasure (PL). As shown in Figure 5, a strong adverse effect of traffic sounds on psychological responses was found, which led to lower comfort, higher annoyance, higher arousal, and lower pleasure compared with the silence group. A MANOVA was conducted to investigate the effect of traffic sounds on the psychological responses, as shown in Table 1. The main effects of acoustic variables, including sound type and the sound level were found to be statistically significant (Sig. < 0.05) with no interactions. Moreover, no significant difference was found between different gender groups.



Figure 5. Effect of sound level on psychological responses. The vertical bar represents 95% confidence interval.

Variables	Psychological Response	F	Sig.	η_p^2
	AC	2.93	0.03 *	0.02
Sound Type	AN	4.58	0.00 **	0.04
	AR	1.40	0.24	0.01
	PL	2.19	0.09	0.02
SPL (L _{Aeq})	AC	80.86	0.00 **	0.32
	AN	98.56	0.00 **	0.36
	AR	75.45	0.00 **	0.30
	PL	74.41	0.00 **	0.30
Gender	AC	0.65	0.42	0.00
	AN	0.66	0.42	0.00
	AR	0.00	0.96	0.00
	PL	0.00	0.96	0.00
Sound Type * SPL	AC	0.38	0.89	0.01
	AN	0.46	0.84	0.01
	AR	0.29	0.94	0.00
	PL	0.17	0.98	0.00

Table 1. Results of multivariate tests of psychological evaluations to traffic sounds. AC, AN, AR, and PL represent the evaluation of acoustic comfort, annoyance, arousal, and pleasantness, respectively. * and ** represent significant difference at 0.05 and 0.01 level, respectively.

As for the sound level, significant differences were observed in all four psychological responses. The effect size factor (η_p^2) indicated that the sound level was the most dominant factor for all four psychological attributes. As shown in Figure 5, the decrease in the sound level led to significant improvements in psychological responses (more comfort, less annoyance, less arousing, and more pleasant). Further pairwise comparison (LSD) showed that differences between any sound levels were significant (Sig. < 0.05) for all psychological attributes. Considering that there were no interactions between the sound type and sound level, this tendency was agreed upon in all traffic sound groups.

Although less influential than the sound level, the sound type factor showed significant impacts on acoustic comfort (F = 2.93, Sig. = 0.03 < 0.05) and noise annoyance (F = 4.58, Sig. = 0.00 < 0.05). However, no significant effects of the sound type on arousal and pleasantness were found. By further pairwise comparison (Figure 6), it was found that the impact of tram sound on acoustic comfort (AC), arousal (AR), and pleasure (PL) was higher than that of road traffic sound (Sig. = 0.004 < 0.05). Meanwhile, for noise annoyance, the impact of tram sound was significantly higher than those of the other three traffic sounds ($p_{R,T} = 0.001$; $p_{C,T} = 0.004$; $p_{H,T} = 0.015$). This result showed that the tram sound had a greater impact on how people perceive the acoustic environment at the same sound level. As shown in Figure 2, the tram sound occurred for the shortest duration in this experiment. Moreover, a negative correlation between the psychological impact of traffic sounds (T > H > C > R) and the duration of the sound (T < H < C < R) can be observed in Figure 6. As discussed in Section 2, the 2 min A-weighted equivalent sound level was used to normalize the acoustic stimuli in this study. Therefore, the shortest sound duration time (tram sound) led to the highest peak sound level. The results in Figure 6 indicate that the effect of traffic sound type on psychological responses might be caused by the peak sound level. Another MANOVA was carried out by replacing the equivalent sound level (LAeq) with the peak sound level (LAFmax) to investigate the influence of the sound level parameters. It was found that the peak sound level (LAFmax) was the only influential factor for all four psychological attributes in this analysis. This result indicated that the impact of traffic sound on the perceived acoustic environment was mainly determined by the peak sound level when the traffic sounds showed significant temporal variations. In terms of sound level index for evaluating the perceptual impact, LAFmax showed better performance than LAeq when both the road traffic sound and the railway sound were considered.



Figure 6. Effect of sound type on psychological attributes. R, C, H, and T represent the road traffic, conventional train, high-speed train, and tram, respectively. The vertical bar represents 95% confidence interval. * and ** represent significant differences in pair-wise comparison (LSD) at a 0.05 level and 0.01 level, respectively.

3.2. Effect of Traffic Sounds on Physiological Responses

Table 2 shows the MANOVA results between experiment variables and physiological responses (mean change in EDA and HR). It was found that the physiological responses were significantly affected by both the acoustic factors and the non-acoustic factors, including sound level, gender, and exposure time. Meanwhile, the interactions between factors, including sound type by sound level and sound type by gender, were also observed to be influential on the change in physiological parameters.

Table 2. MANOVA results of physiological evaluations to traffic sounds. * and ** represent significant difference at 0.05 and 0.01 levels, respectively.

Variables		HR			EDA	
	F	Sig.	η_p^2	F	Sig.	η_p^2
Gender	60.389	0.000 **	0.03	57.247	0.000 **	0.03
Time	2.699	0.019 *	0.01	0.113	0.989	0.00
Sound Type	0.456	0.713	0.00	2.293	0.076	0.00
SPL	6.033	0.002 **	0.01	3.615	0.027 *	0.00
Sound Type * SPL	2.365	0.028 *	0.01	2.835	0.009 **	0.01
Sound Type * Gender	0.261	0.853	0.00	6.079	0.000 **	0.01
Sound Type * Time	0.102	1.000	0.00	0.006	1.000	0.00

In terms of acoustic factors, the sound level showed significant influences on both EDA (F = 3.615, Sig. = 0.027) and HR (F = 6.033, Sig. = 0.002). The main effect of the sound type was found to not be significant on neither EDA (F = 2.293, Sig. = 0.076) nor HR (F = 0.456, Sig. = 0.713). Instead, significant interaction effects of sound type and sound level were observed on EDA (F = 2.835, Sig. = 0.009) and HR (F = 2.365, Sig. = 0.028). In general, this result indicated that the sound level played a more important role in the physiological impact of traffic sounds than the sound type. However, the tendencies between sound level and physiological indicators might be different for different traffic sounds. Therefore, a pairwise comparison by nonparametric Mann–Whitney U test was applied.

Figure 7 shows the relationship between the sound level and physiological indicators in different sound groups. From the pairwise comparison in the Mann–Whitney U test, significant differences were identified in each traffic sound group with the variation in the sound level. All the significant differences were found within the road traffic sound group (R) and high-speed train group (H). As for EDA, two significant differences were observed: (1) road traffic sound: a significant decrease with SPL increased from 55 dB to 65 dB ($\chi^2(1) = 2.227$, p = 0.026); (2) high-speed train sound: a significant increase with SPL increased from 45 dB to 65 dB ($\chi^2(1) = 2.320$, p = 0.020). As for HR, three significant differences were observed: (1) road traffic sound: a significant increase with SPL increased from 45 dB to 65 dB ($\chi^2(1) = 3.605$, p = 0.002); (2) road traffic sound: a significant increase with SPL increased from 55 dB to 65 dB ($\chi^2(1) = 2.807$, p = 0.005); (3) high speed train sound: a significant increase with SPL increased from 45 dB to 65 dB ($\chi^2(1) = 2.662$, p = 0.008).



Figure 7. Interaction effect of sound level and sound type on EDA and HR. The vertical bar represents 95% confidence interval. * and ** represent significant differences in the Mann–Whitney U test at a 0.05 level and 0.01 level, respectively.

This result showed that the influence of the sound level on physiological responses depended on the sound type. In general, the relationship between the sound level and physiological parameters could be divided into two categories: (1) sound-level-sensitive group: road traffic sound (R) and high-speed train (H); (2) sound-level-insensitive group: conventional train (C) and tram (T). For the conventional train (C) and tram (T), the variation in sound level from 45 dB to 65 dB hardly affected the change in participant's physiological indicators. In contrast, considerable impacts on physiological responses were observed by the increase in sound level of road traffic sound (R) and high-speed train sound (H). This phenomenon was the same in both EDA and HR. As for HR, the tendency was agreed in the road traffic group (R) and tram group (T) that HR increased with the increase in sound level. However, the increase in sound level led to the increase in EDA under high-speed train sound (H) and the decrease in EDA under road traffic sound (R). It was also found that all the significant differences were caused by increasing the sound level to 65 dB, although the influence of the change between 45 dB and 55 dB was minimal. This result indicated that the subjects were more physiologically sensitive to the sound level when expose to high-level traffic sounds.

As for non-acoustic factors, the main effect of gender and exposure time was found to be influential on the participant's physiological responses. Regarding the effect size, gender was found to be the most influential factor for both EDA and HR ($\eta_p^2 = 0.03$). As shown in Figure 8, the changes in HR and EDA of male subjects were lower and higher than those of female subjects, respectively. Significant effects of exposure time on HR (F = 2.699, Sig. = 0.019) are exhibited in Figure 8, where no effect on EDA (F = 0.113, Sig. = 0.989) was found. With the increase in exposure time, HR significantly decreased by approximately 3% in the first 60 s, and gradually steadied after 80 s.



Figure 8. Effect of gender and exposure time on physiological responses to traffic sounds. The vertical bars represents 95% confidence intervals.

In addition, an interaction effect of gender and sound type was observed on EDA, as shown in Figure 9. In pairwise comparison by the Mann–Whitney U test within each gender group, three significant differences were observed: (1) the EDA of males under high-speed train sound was significantly lower than that under the tram sound ($\chi^2(1) = 2.323$, p = 0.020); (2) the EDA of female participants under high-speed train sound was significantly higher than that under the conventional train sound ($\chi^2(1) = 2.267$, p = 0.023); and (3) the EDA of female participants under high-speed train sound was significantly higher than that under the road traffic sound ($\chi^2(1) = 2.142$, p = 0.032). In general, exposure to high-speed train sound led to lower and higher EDA for male and female subjects, respectively. This result indicated that the impact of the high-speed train sound on EDA response was different from those of other sounds, which also agreed with the results in Figure 7.



Figure 9. Interaction effect of gender and sound type on EDA. R, C, H, and T represent the road traffic, conventional train, high-speed train, and tram, respectively. The vertical bar represents 95% confidence interval. * represents significant difference in the Mann–Whitney U test at a 0.05 level.

3.3. Relationship between Psychological and Physiological Responses

A correlation analysis was applied to reveal the relationship between the psychological responses and physiological responses for the 12 experiment stimuli. As shown in Table 3, all four psychological responses were highly correlated with each other (r = 0.986~0.998, p < 0.01), which indicated that the psychological evaluations of the traffic sounds (AN, AR, and PL) had considerable influences on the evaluation of the overall acoustic environment (AC). It was also found that the HR was significantly correlated with all four psychological dimensions (r = 0.624~0.691, p < 0.05). A lower perceptual impact of sound (more comfort, less annoying, less arousal, and more pleasant) led to lower HR, as shown in Figure 10. However, the EDA was found to be independent of the psychological responses and the HR.

Table 3. Correlation analysis between psychological and physiological responses. * and ** represent significant correlations at 0.05 and 0.01 levels, respectively.

Pearson Correlation		Psychological				Physiol	Physiological	
		AC	AN	AR	PL	EDA	HR	
Psychological	AC	1.000						
	AN	-0.986 **	1.000					
	AR	-0.993 **	0.986 **	1.000				
	PL	0.992 **	-0.987 **	-0.998 **	1.000			
Physiological	EDA	-0.092	0.131	0.064	-0.062	1.000		
	HR	-0.689 *	0.624 *	0.691 *	-0.687 *	0.124	1.000	



Figure 10. Relationship between psychological response (annoyance) and physiological responses. R, C, H, and T represent the road traffic, conventional train, high-speed train, and tram, respectively.

This result was based on the analysis of all four considered traffic sounds, which could be different in different traffic sound groups, as shown in Figure 10. Strong positive correlations between annoyance and physiological responses were observed in the high-speed train group (H). However, for the tram (T) and the conventional train group (C), the noise annoyance was independent of both the EDA and the HR. As for the road traffic sound (R), the noise annoyance was highly correlated with the HR, as shown in Figure 10. As discussed in Sections 3.1 and 3.2, the psychological responses were dominated by the sound level. Meanwhile, the physiological responses were also significantly affected by the interaction of the sound type and the sound level. Therefore, only weak correlations were found between the psychological responses and the physiological responses which varied in different sound groups.

4. Discussion

As for psychological evaluations, it was found that the traffic sounds brought considerable impacts on the acoustic environment in office space, which constantly increased with the increase in sound level. This result indicated that the control of traffic sound level was efficient for reducing the psychological impact at any sound level, which agreed with the dose–response curve established by the long-term field survey [59,60]. In addition, significant effects of the sound type on acoustic comfort and noise annoyance were also found, which were further revealed to be caused by the peak sound level. In this study, both the continuous sound (road traffic sound) and the intermittent sound (railway sound) were considered in the short-term sound exposure experiment. Under this condition, the peak sound level was more appropriate for evaluating the perceptual impact of sounds. This result agreed with the result in the literature in other indoor spaces [61]. However, if the analysis was conducted focusing on one single traffic sound source, for instance, the high-speed train sound, the equivalent sound level representing the average energy of the sound might be more appropriate because the temporal structures of sounds were similar. The results in this study indicated that for evaluating the perceptual impact of short-term traffic sound exposure, the peak sound level could be used as a common index for different traffic sounds, instead of setting an adjusting factor according to the sound type.

As for physiological responses, a complex interaction effect of acoustic factors and nonacoustic factors on physiological indices was found. In general, the sound level showed significant influences on both the EDA and HR. Regarding the road traffic sound, the increase in sound level led to higher HR and EDA levels, which agreed with most results in the existing literature [35,37,40].

However, different from the existing literature, the physiological impacts of three railway sounds were also examined and compared with road traffic sound in this study. The results showed that the influence of the sound level on physiological responses depended on the sound type. As for the conventional train and tram, the influence caused by sound level variation from 45 to 65 dB hardly affected the participant's HR and EDA. In contrast, the sound level was found to be influential in the road traffic group and the high-speed train group on HR and EDA. The results in this study revealed the importance of sound source recognition for evaluating the physiological impact of traffic sounds. It was also reported in the literature that the effect of other sound, for example, sound in hospitals [62], environmental sounds [23], and floor impact sounds [63], could be very different from continuous sounds. In the field of soundscape research, when multiple sound sources are considered, including artificial sounds, natural sounds, and music, it was suggested that the sound source was a dominant factor to determine the physiological effect of the acoustic environment [41,53,64]. Some other long-term exposure studies also found a difference between road traffic and railway sound, in which the road traffic sound and railway sound showed different impacts on other physiological parameters (blood pressure) [65].

Relative weak correlations between the psychological responses and physiological responses under the impact of traffic sounds were found in this study, which were also affected by the sound type. The HR was found to be significantly correlated with psychological evaluations of the sound, whereas lower HR was found under the exposure to less annoying, less arousing, and less unpleasant sounds. Similar results were also reported in relevant soundscape studies, in which pleasantness and eventfulness were found to be correlated with the HR and EDA [25,66]. Although significant associations were found, the results in this study showed that the physiological responses, which indicated the potential long-term health effect, could not be fully predicted by the self-reported psychological responses. Therefore, to comprehensively investigate the traffic sound impact, the collection of physiological responses might be necessary.

In general, the results in this study showed that the psychophysiological effects of traffic sounds on people were different. One main reason for this phenomenon is the difference in temporal characteristics. As the spectrogram shows in Figure 2, the major difference between road traffic sound and railway sounds was the duration time. The results in Section 3 further proved that the differences in duration time led to differences in psychological responses. As for the physiological responses, results in this study also found that there were significant differences between the continuous traffic sound (road traffic) and the intermittent sounds (railway sounds). However, it should be noted that some of

the results could not be fully explained by the temporal characteristics. In Section 3, the high-speed train sound was found to have different physiological effects on people when compared with other railway sounds. However, the duration of high-speed train sound was similar to that of the tram sound. In addition to temporal differences, the spectral differences between different traffic sounds were also observed in this study. As shown in Figure 2, there were more high-frequency components in high-speed train sounds than in other railway sounds. Moreover, there were significant concentrations of magnitudes in the beginning and the end of the stimuli in the conventional train and tram sounds. The combination of spectral and temporal characteristics made the participants be able to recognize the traffic sound type, which could not be simply described by the sound level and duration time.

Regarding the sound control treatments, the results in this study revealed that the decrease in the sound level did not necessarily lead to the reduction in the impact from traffic sounds, because the physiological responses for some traffic sounds (conventional train and tram) were not sensitive to the sound level. Therefore, different strategies should be especially designed according to the sound type. As for the road traffic sound and the high-speed train sound, the sound control treatments, for instance, sound barrier, could be efficient both psychologically and physiologically. However, for conventional train and tram, such treatments hardly reduced the sound impact on the residents' physiological state. It has been found that the presence of natural sounds, including bird singing and water sound, could improve perceptual evaluations of the acoustic environment. Moreover, it was suggested that in the mixed soundscape, the physiological responses were correlated with the pleasantness of the overall acoustic environment [25]. A positive physiological effect of birdsong mixed with road traffic sound was reported in [38]. Therefore, introducing pleasant natural sound elements might be a potential solution for masking the physiological impacts of conventional train and tram sound.

This study also has some limitations. First, silence was chosen as the baseline condition to investigate the fundamental effect of traffic sounds on people in offices. Therefore, the scenario considered in this study was more related to offices in which traffic sounds are the dominant sound sources, including offices very close to traffic lines and quiet single working spaces (for instance, home working spaces). However, there are inevitable other sound sources in office spaces, which also have significant impacts on people [6]. As for open-plan offices, conversation sounds were reported to be the most influential sound source on the perception of acoustic quality and work-related quality [2]. Therefore, in offices with multiple sound sources, the effect of traffic sounds might be different. Future studies need to be conducted to investigate the effect of combined sounds on people in such office spaces. Second, the experimental stimuli in this study were collected adjacent to the traffic lines to avoid accidental environmental sounds. However, there were inevitable differences between the recorded traffic sounds and the sounds received inside the offices because the reflections and absorptions were not considered. In future studies, the interaction effect of traffic sound characteristics and indoor acoustic quality could be further investigated. Third, the sound level equalization of experimental stimuli was carried out without using a head and torso simulator, which could lead to errors in the traffic sound levels.

5. Conclusions

A laboratory experiment on the psychophysiological responses to traffic sounds was conducted in this study. MANOVA was applied to identify the influential factor that had significant effects on the psychophysiological responses. The following results were obtained:

(1) The traffic sounds brought considerable impacts on the psychophysiological responses of the acoustic environment in office space, which depended on the sound type. Without considering the interaction with other indoor noises, all traffic sounds were found to have adverse psychological effects on the overall acoustic environment. As for the physiological responses, the effect of sound type was found to interact with the sound level and non-acoustic factors (gender);

- (2) The sound level was found to be the most influential factor on the psychophysiological responses. The negative effects of traffic sounds on psychological responses were found to constantly increase with the increase in the sound level. The peak sound level showed better performance than the equivalent sound level in evaluating the perceptual impact of short-term sound exposure. The relationship between sound level and physiological parameters varied among different sound groups. The variation in sound level hardly affected the participants' HR and EDA when exposed to the conventional train and tram sound. In contrast, HR and EDA were significantly affected by the levels of road traffic sounds and high-speed train sounds;
- (3) Non-acoustic factors were found to be influential on the physiological responses. The HR was found to decrease with the increase in exposure time. Gender was found to be an important factor of the physiological parameters, which also had an interaction effect with the noise level;
- (4) Relatively weak correlations between the psychological evaluations and HR were found, whereas the relationship between the psychological attributes and EDA was found to be significantly affected by the sound type.

Although the current study was based on a laboratory experiment, the results presented in this study may serve as a supplementary tool for architects, planners, and city managers to estimate not only the impact of traffic sounds on the urban environment, but also the effectiveness of noise treatments. Future research will focus on how to reduce the impact of traffic sounds, including (a) the effect of sound barriers on the psychophysiological responses when exposed to traffic sounds; (b) effectiveness of soundscape treatments on masking traffic sounds, for example, introducing natural sounds to reduce the impact brought by traffic sounds.

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