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Effect of the Exterior Traffic Noises on the Sound Environment Evaluation in Office Spaces with Different Interior Noise Conditions

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Abstract: The present study focuses on the impact of exterior traffic noises on sound environment evaluation in office spaces, considering their interaction with interior noises. There were three interior noise conditions: silence, air-conditioner noise, and irrelevant speech noise. Six exterior traffic noises (road, maglev, tram, metro, conventional inter-city train, and high-speed train) were merged with interior noise clips to create the combined noise stimuli. Forty subjects participated in the experiment to assess the acoustic environment in office spaces exposed to multiple noises. The results showed that both interior and exterior noise significantly affected acoustic comfort and noise disturbance. As for the exterior traffic noise, both the traffic noise source and the noise level were found to be influential on both attributes. More temporally fluctuating traffic noises, such as high-speed train noise, were found to have a greater negative effect on subjective evaluations. Meanwhile, the interior noise source was also found to influence evaluations of the sound environment. Compared to the single traffic noise condition, irrelevant speech noise significantly increased the negative impact of traffic noises, while the air-conditioner noise had a neutral effect. In addition, participants in offices with speech noise were less sensitive to the traffic noise level.

Keywords: rail traffic noise; acoustic comfort; noise disturbance

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1. Introduction

With the rapid development of urbanization, the demand for office space in cities has significantly increased. The quality of the acoustic environment in the office space becomes a critical factor affecting the work performance and well-being of the workers [1]. Noise has been proven to have considerable negative effects on workers' moods, efficiency, and even long-term health [2,3].

Numerous field measurements and questionnaire surveys have described the objective characteristics of and subjective responses to noise in office environments. Most field measurements have primarily focused on sound level indicators, including the A-weighted equivalent sound level (L_{Aeq}) and percentile levels (L_{10}, L_{50}, L_{90}, etc.), to describe the spatial and temporal characteristics of background noise levels [4,5]. It has been found that there is a significant variation in noise levels which is highly dependent on the office type [4,6]. In enclosed offices, where employees are separated by walls or panels, have resulted in a relatively low noise level [7–9]. In open-plan offices, as the volume of space and the number of workers tend to be higher, more noise sources have been identified, leading to higher noise levels [10,11].

In addition to the noise level, the noise source has been proven to be a crucial factor in determining how people perceive the sound environment [12]. A questionnaire survey is the most common method to document the response of workers to various sound sources. As reported, human-generated sounds (speech, footsteps, etc.), mechanical sounds (keyboard, printer, ventilation, etc.), and music have been identified as the primary interior sound sources in office spaces [13–15]. The telephone ringing and speech noise have been reported as the most frequently perceived and the most annoying noise sources, respectively [9,16–18]. Meanwhile, continuous noises, such as air-conditioner noise, are generally considered to cause little annoyance. Traffic sounds, construction sounds, and natural sounds have been reported as the most common exterior sound sources [19]. Among these sound sources, road traffic noise has been suggested to be one of the major sources of disturbance to daily work activities [20,21].

In most previous studies, people have been found to be more frequently annoyed by interior noises than traffic noises when comparing different noise sources [15,19]. Due to the building envelope, the exterior noise level is significantly lower than speech noise, especially in open-plan offices. Therefore, speech noise is commonly identified as the most influential noise source. However, for enclosed offices and offices located near traffic lines, the annoyance caused by traffic noise might increase due to the rise in traffic noise levels or the reduction in noise level of other noise sources [22]. Based on a field survey, it was reported that 81% of workers near the major streets were annoyed by traffic sounds [20]. Zhang et al. [23] reported that people were more annoyed by exterior noises than interior noises in high-rise offices, especially in areas with a heavy road traffic flow. For individuals who work from home, traffic noise has been reported as the second most annoying source of noise [24]. Measuring the sound level of each sound source in a field survey is very challenging. Therefore, disagreements in the effects of noise sources could be found in the existing studies.

In contrast to field surveys, laboratory experiments are commonly used to measure how subjects respond to controlled stimuli. A laboratory experiment was conducted to compare the restorative effects of various sound sources in an office environment [25]. It was found that the negative impact of traffic noise is significantly greater than that associated with air conditioners at the same noise level. Meng et al. [26] compared the effects of traffic noise and air-conditioning noise on visual cognitive performance in office spaces. Haghighat et al. [27] conducted a laboratory experiment comparing the effects of non-verbal noise and verbal noise on subjective evaluations and cognitive performance in office spaces. Jahncke [28] suggests that interior noises with phone and speech signals may have a significant influence on cognitive performance and self-reported restoration, while no significant effects on physiological indicators were found.

Based on laboratory experiments, the quantitative relationship between noise characteristics and the effects of noise on people can be analyzed. Most existing laboratory studies, however, use a single noise source as the experimental stimulus, an approach which is less realistic. In most office environments, interior and exterior noises coexist [29]. It has been proven that the impact of combined noises is significantly different from that of single-source noises [30–32]. However, few studies have investigated how the combined interior and exterior noises affect workers in an office environment.

Moreover, most existing studies focusing on office spaces have primarily examined road traffic noise, with very few addressing rail traffic noises. It is reported that there are significant differences between road and rail traffic sounds in terms of acoustic characteristics, especially temporal characteristics [33,34]. In quiet spaces, such as dwellings, numerous studies have shown that the impact of rail traffic noise on individuals significantly differs from that of road traffic noise [35]. Even amidst rail traffic noises, high-speed trains have been found to have a significantly greater impact than conventional trains [36]. So far, the impact of different traffic noises on office spaces remains uncertain. In contrast to residential spaces, exterior traffic noise is commonly mixed with interior sounds in office spaces. With respect to combined noises, it has been found that temporal evolution is a crucial factor in determining how people perceive the combined noises [31]. Therefore, it is reasonable to assume that variations in traffic noises will lead to differences in their impact on the evaluation of the office sound environment when combined with interior noises.

Based on the analyses from previous studies, the research questions for this study are as follows:

1. How do exterior traffic noises affect the evaluation of the acoustic environment in office spaces? Are there significant differences among various traffic noise sources?
2. What are the effects of interior noises on people exposed to exterior traffic noises? Are there significant differences among various interior noise conditions?

In the present study, we conducted a laboratory experiment to investigate the subjective perception of 40 participants under various combined noise configurations. The effects of interior noise (IN), traffic noise source (TN), and traffic noise level (SPL) on noise disturbance and acoustic comfort were examined. This paper is organized as follows. The experiment implementation is shown in Section 2. Section 3 presents the results that reveal the influential factors affecting subjective evaluations of the acoustic environment when exposed to combined sounds. In Section 4, the results of this study are discussed with respect to relevant studies. Section 5 summarizes the main findings of this study.

2. Materials and Methods

2.1. Experimental Condition

A laboratory experiment was conducted to investigate the interaction between interior noise and exterior traffic noise in office spaces. The physical environment was controlled to rule out the influence of other factors (temperature = 23~25 °C; background sound level < 30 dBA).

Figure 1 shows the layout of the experimental environment. A baffle was positioned between the operator and the participants to prevent visual contact. The participants were asked to complete a letter retrieval task during the experiment. Specifically, they were required to mark all the letters 'a' in a reading material from the College English Test.

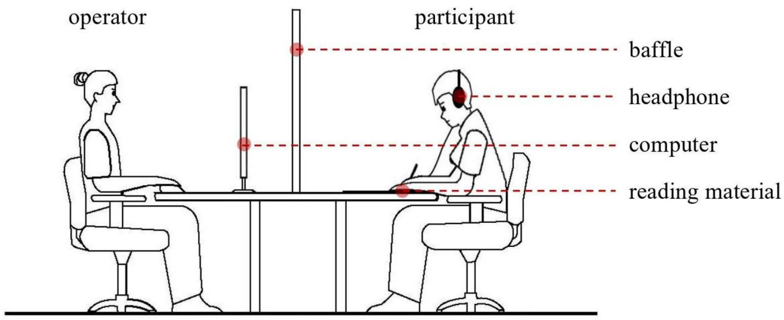

Figure 1. Experimental environment setup.

During the experiment, the participants were exposed to sound stimuli using a combination of a computer, a power amplifier, and a reference class headphone (650HD, Sennheiser, Germany) to ensure the spectral accuracy of the emitted signal.

2.2. Experiment Stimuli

According to the research goal, there were three variables in the experiment: interior noise source (IN), traffic noise source (TN), and traffic noise level (SPL). To control the sound level of each noise source in the combined noise approach, four steps were used to create the experimental stimuli.

(1) Field recording

All sound materials were field recorded in Beijing, China. The experiment included nine noise sources: three interior noises and six traffic noises.

Three interior noise conditions were considered in this study: silence (SL), air-conditioner noise (AC), and irrelevant speech noise (IS). The air-conditioner noise was recorded in an empty open-plan office to eliminate other sound sources, as shown Figure 2. The microphone was placed three meters away from the air outlet. The velocity was set to medium, and a 30 min recording was collected after the air-conditioner noise stabilized. The irrelevant speech noise was recorded in a busy city office (volume = 500 m^3; number of people = 50~100). The sound recorder was placed 20 m away from the nearest office counter to prevent capturing clear voices from the visitors and officers. Longer recordings (4 h) were collected to extract clear speech clips without ambient noises.

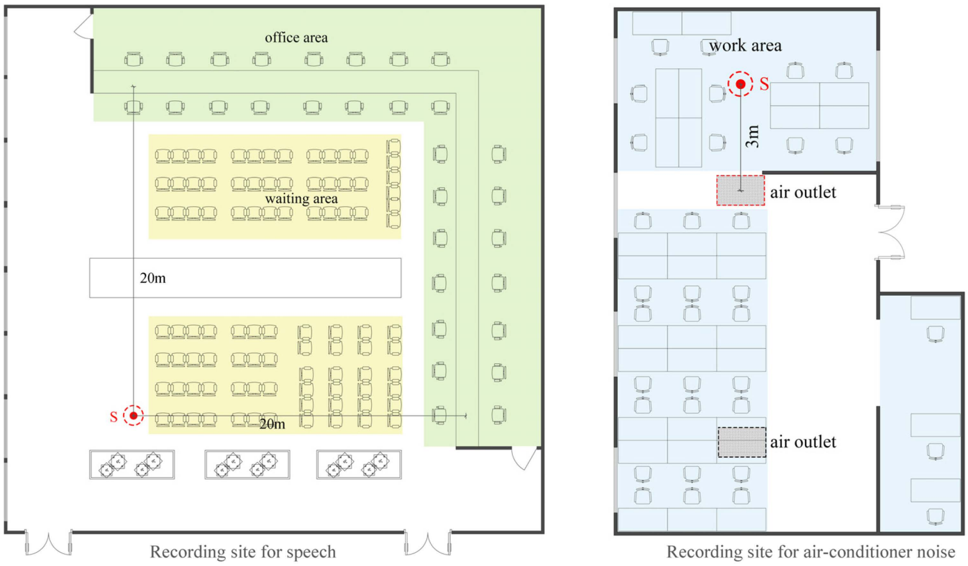

Figure 2. The layout of the field recording site for speech noise and air-conditioner noise (S indicates the position of the recorder).

As for the traffic noises, there are two main methods for field recording. Some of the previous studies, e.g., Reference [37], have placed the recorder near the building facades. By measuring the sound insulation effect of building facades, it is possible to replicate the traffic noise situation inside the building. This method is highly accurate for simulating the noise conditions at a specific location. However, the recordings could be easily affected by ambient noise because the recording sites are very close to the building facades. An alternative method is to record the sound near the traffic line [38]. This method is quite useful for laboratory studies that compare the effects of different sound sources because the influence of ambient noises can be easily avoided. Moreover, it also allows for modifications to be applied to the original signals to simulate the effect of the sound propagation process.

In this study, road traffic noise and five types of rail traffic noises were considered, including maglev (Ma), tram (T), metro (Me), conventional inter-city train (C), and high-speed train (H). To avoid ambient noises, the sound recording was carried out in quiet areas near the traffic line. The recorder was placed approximately 10 m from the traffic line and 1.25 m above the ground.

A sound meter (6228+, Aihua, Hangzhou, China) was used to conduct sound recording and measurement under the same format (48 kHz, single-channel, 16 bits).

(2) Sound clip extraction

The field recordings were then manually rechecked to extract a clear sound clip for each sound condition. As shown in Figure 3, the noise recordings showed significant differences in temporal characteristics. The air-conditioner noise was quite steady. There were short-term fluctuations in the speech noise and the road traffic noise. Rail traffic noises peaked when the train passed by, causing significant temporal fluctuations in the recordings. The duration of the peak varied from 20 to 40 s, depending on the rail type. Therefore, a 1 min clip for each noise source was extracted from the field recordings. For air-conditioner, speech, and road traffic noises, continuous clips without other noise sources were extracted. As for the five rail traffic noises, the extraction was conducted based on two principles: (a) there were no other noises present, (b) there was only one train passing by in the middle of the 1 min clip.

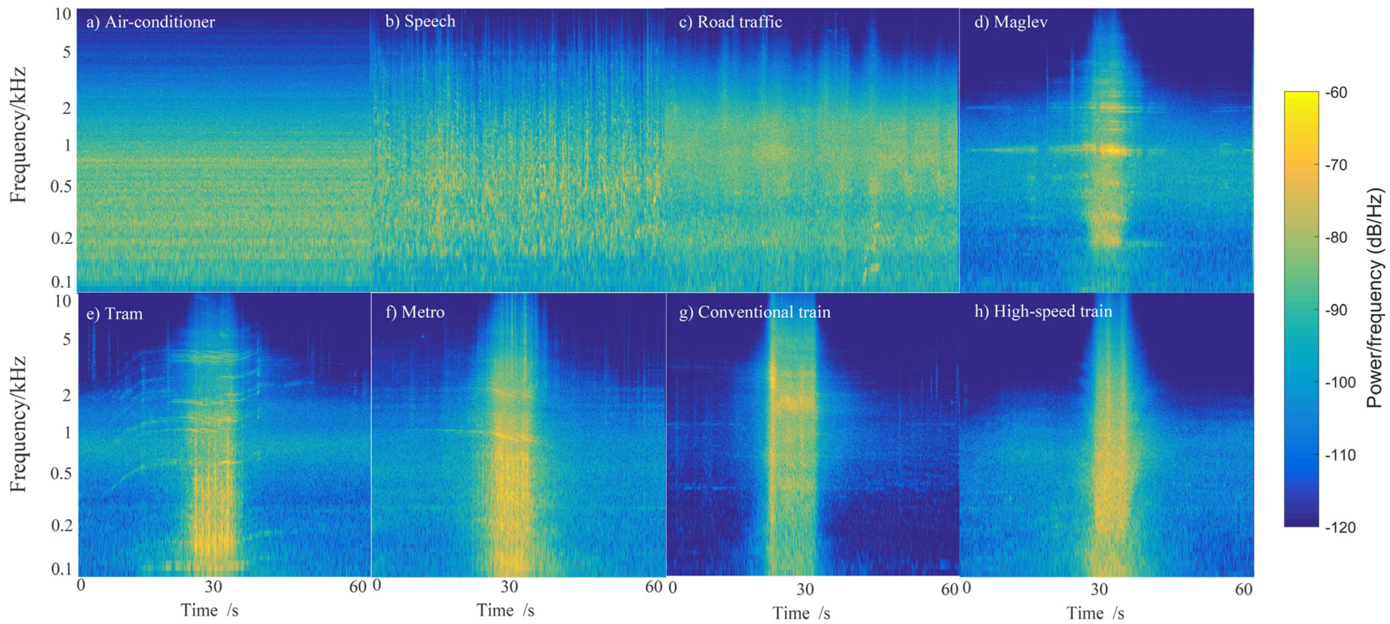

Figure 3. Spectrogram of noise clips extracted from the field recordings.

For the exterior traffic noise clips, a filter with frequency responses that mimicked the effect of sound insulation on building facades was applied. Daniel et al. [37] measured the sound insulation index of 31 window elements in 1/3-octave bands ranging from 50 Hz to 5000 Hz. The sound insulation levels from three apartment building facades were also reported in Reference [38]. The frequency characteristics reported in the two studies were quite similar. Therefore, the detailed data from Reference [37] were used to design the filter in this study, as illustrated in Figure 4. For frequencies below 50 Hz and above 5000 Hz, the attenuation was designed based on the 50 Hz and 5000 Hz bands, respectively. The sound filtering was applied using the graphic equalizer tool in the Audition software (2020) [38]. The spectrogram of the filtered exterior noise clips is shown in Figure 5.

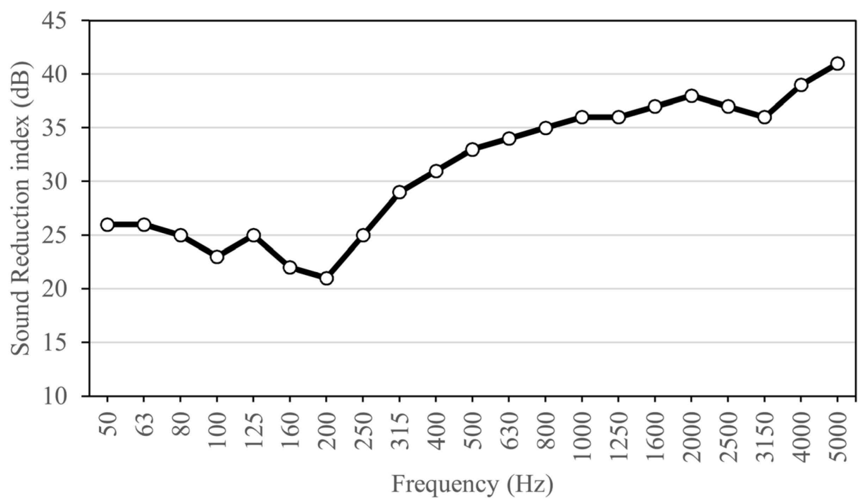

Figure 4. Sound reduction index of the filter applied to exterior traffic noises, simulating the sound insulation afforded by the building facade (data from [37]).

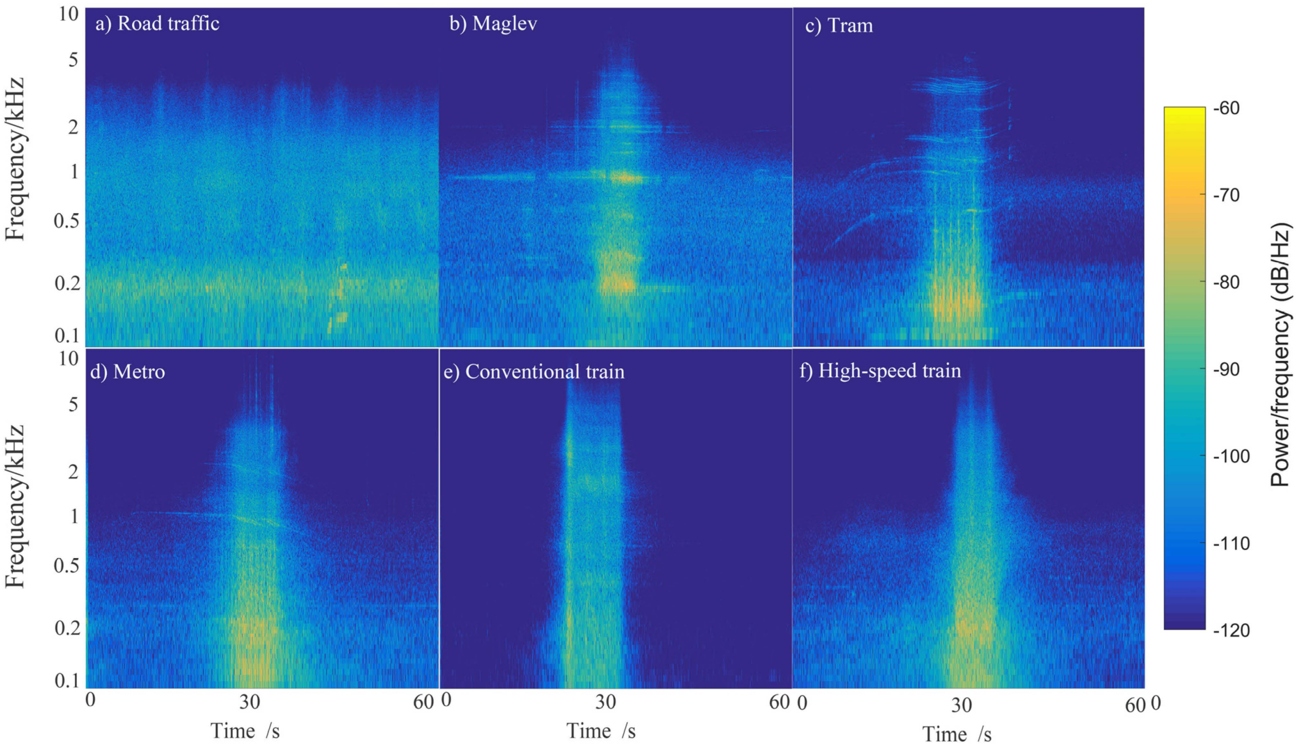

Figure 5. Spectrogram of exterior traffic noise clips after filtering and sound level calibration ($L_{Aeq,1\,min}$ = 40 dB).

(3) Sound level calibration

Based on the field measurements and data reported in previous studies, the noise level of common office spaces was found to vary from 40 dB to 55 dB [26,39]. Two sound levels ($L_{Aeq,\,1\,min}$) were considered for the traffic noises: 40 dB and 50 dB. Because six different traffic noise sources were considered in this study, there were 12 traffic noise clips in total. The sound level of the interior noises was set to 40 dB.

The sound level calibration was conducted using a head and torso simulator (Brüel & Kjær 4128-C, Denmark). The volume of each stimulus was adjusted until the sound level reached the intended level. In addition, we also examined the frequency response of the reproduced signal. At the frequency range of most sound energy (50 Hz to 4000 Hz), the differences caused by the sound reproduction system were smaller than 3 dB. The sound levels of frequency bands above 5000 Hz were lower than 25 dB, which was close to the background level. Therefore, it could hardly affect the participants' evaluation, even though there were relatively larger differences (5 dB to 10 dB) between the designed and the reproduced signal.

In this study, the stimuli were calibrated at the same equivalent sound level ($L_{Aeq,1\,min}$). However, the peak sound levels in the noise clips varied due to temporal differences. As shown in Table 1, the peak sound level (L_{Afmax}) varied from 45.7 dB to 56.2 dB at the same equivalent sound level (40 dB). To quantify the temporal fluctuation characteristics, L_{10}–L_{90} values were calculated. L_{10} and L_{90} are commonly used to measure the sound levels of noise events and background sounds, respectively. Therefore, L_{10}–L_{90} describes the sound level difference between the noise event and the background sound. As shown in Table 1, the L_{10}–L_{90} of road traffic noise was relatively low (2.63) due to its consistent temporal pattern without significant noise events. On the contrary, there was a distinct noise event in each rail traffic noise clip, leading to more temporal fluctuations and significantly higher L_{10}–L_{90} values (17.5–23.2). As vehicle speed increased and vehicle length decreased, the duration of sound events in rail traffic clips decreased, resulting in a greater temporal fluctuation.

Table 1. Acoustic characteristics of single sound clips in the experiment.

Category	Noise Source	Vehicle Speed Km/h	Vehicle Length/m	L_{Aeq}/dBA	L_{Afmax}/dBA	L_{10}–L_{90}/dBA
Interior noise	AC	–	–	40	40.33	0.76
	IS	–	–	40	43.04	5.41
Traffic noise	R	<60	–	40/50	45.7/56.3	2.63
	Ma	<100	90	40/50	52.0/62.4	17.5
	T	<30	32	40/50	53.5/63.6	21.9
	Me	<80	120–150	40/50	51.9/61.3	22.6
	C	<120	200–300	40/50	56.2/66.0	22.4
	H	<350	200	40/50	51.5/61.3	23.2

(4) Experiment stimuli production: combination of traffic sounds and interior noises

The experimental stimuli with combined noises were created by blending traffic sound clips with interior noise clips. There were three interior noise conditions: SL (silence), AC (air conditioner), and IS (irrelevant speech). For each interior noise condition, twelve traffic noises were considered as exterior noise conditions, including six traffic noises at two sound levels (40 dB and 50 dB). Therefore, there were 36 sound stimuli in this experiment, as illustrated in Figure 6.

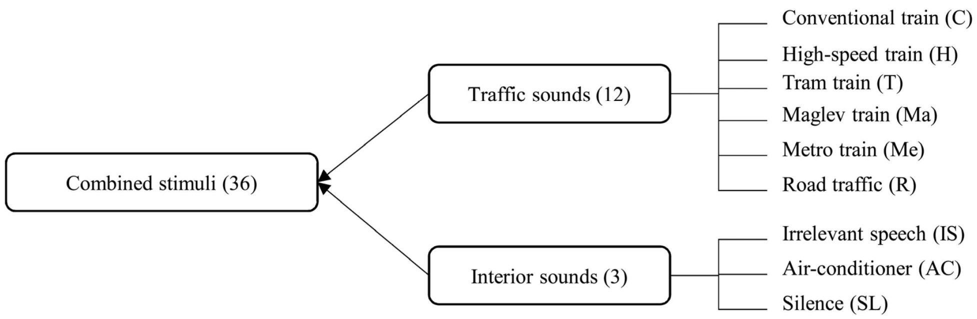

Figure 6. Setup of the combined noise stimuli.

2.3. Subjective Evaluation Measurement

During the experiment, a questionnaire was used to guide the participants. The questionnaire included two attributes to assess the impact of noise stimuli: acoustic comfort and noise disturbance [40].

The first attribute was noise disturbance. Work disturbance is a significant issue caused by noise in office spaces [41]. In this study, the participants were asked to perform a letter retrieval task to simulate the situation in an office environment. After each noise stimulus, the participants were asked to evaluate the level of disturbance caused by the noise using a five-point verbal scale. The verbal marks were: (1) "Not disturbing at all", (2) "slightly disturbing", (3) "moderately disturbing", (4) "very disturbing", and (5) "Extremely disturbing". A higher value in the noise disturbance evaluation indicates that the participant was more disturbed during the experiment.

In addition to noise disturbance, acoustic comfort was also used as a metric to assess the quality of the overall sound environment [12]. As suggested by Della et al., acoustic comfort is a complex aspect that can provide a comprehensive understanding of how people perceive the acoustic environment [42]. During the experiment, participants were instructed to evaluate the overall experience of the acoustic environment rather than the response to a single noise source. A five-point scale with verbal descriptors suggested by Yang and Kang was used [43]: (1) "very uncomfortable", (2) "uncomfortable", (3) "neither comfortable nor uncomfortable", (4) "comfortable", and (5) "very comfortable". Thus, a higher value of the acoustic comfort evaluation indicates that the participant felt more comfortable in the office environment.

2.4. Participants

Forty subjects aged 20 to 29 participated in the experiment. All subjects were university students from Beijing Jiaotong University. All of them had normal hearing. None of the subjects consumed alcohol, tea, or coffee within 8 h before the experiment. All participants were informed about the experiment, including the stimuli, the procedure of the experiment, and the potential risks involved. All participants volunteered to take part in the experiment.

2.5. Experimental Procedure

As shown in Figure 7, the experiment included two parts: (1) experimental preparation and (2) formal experiment. Personal information (name, gender, and age) was collected after the participants arrived at the laboratory. The purpose and structure of the experiment were then communicated to the participants. After wearing the headphones, four practice stimuli were played: silence, a single air-conditioner noise, a single irrelevant speech noise, and silence. Then, there was a 1 min break to eliminate the influence of practice stimuli. The preparation phase lasted for about 15 min.

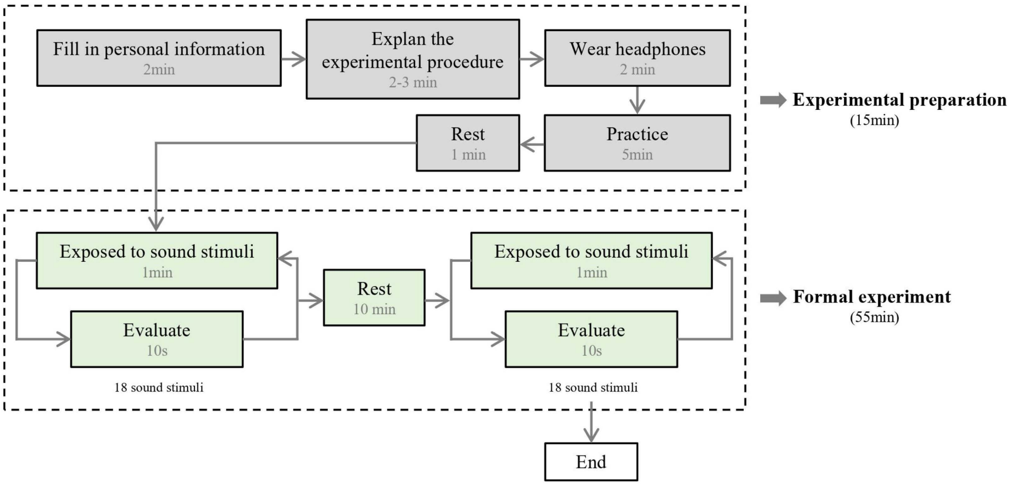

Figure 7. Experimental procedure.

During the formal experimental phase, sound stimuli were presented after the participants had begun reading the material. After being exposed to 1 min clips of the sound stimuli, the participants assessed the acoustic comfort and noise disturbance by completing a questionnaire on the desk within 10 s. A total of 36 sound stimuli were played in a unique random order for each participant. There was a 10 min break during the experiment after 18 stimuli had been delivered. The total time for the formal experiment was about 45 min, excluding the break time.

2.6. Statistical Analysis

Data were analyzed using the SPSS 20.0 software (Statistical Product and Service Solutions, IBM, Chicago, IL, USA). A multivariate analysis of variance (MANOVA) was initially employed to identify the factors of combined noises influencing subjective evaluations of office space. In this study, there were three independent variables: indoor noise (IN), traffic noise type (TN), and traffic sound level (SPL). Effects included main effects and interaction effects. We examined the homogeneity of variance using the Levene's test. The least significant difference test (LSD) was conducted in pairwise comparisons to identify significant differences between groups. The correlation analysis was used to examine the relationship between the acoustic comfort evaluations and noise disturbance evaluations. A p-value less than 0.05 was used as the criterion to determine significant differences.

3. Results

Table 2 shows the results from the MANOVA analysis. First, the main effects of TN and SPL on both acoustic comfort and noise disturbance were found to be significant, with no interaction effect. Meanwhile, the main effects of IN were also found to be significant in both evaluations. Furthermore, the interaction effect between the interior noise source (IN) and traffic sound level (SPL) was also significant in both subjective evaluations.

Table 2. MANOVA analysis for the effects of interior noise (IN), traffic noise type (TN), and traffic noise level (SPL) on subjective evaluations of the sound environment. The symbols '*' and '**' represent significance at 0.05 and 0.01 levels, respectively.

	Acoustic Comfort			**Noise Disturbance**		
	F	**Sig.**	η_p^2	**F**	**Sig.**	η_p^2
IN	40.87	0.00 **	0.06	37.59	0.00 **	0.05
TN	5.35	0.00 **	0.02	8.73	0.00 **	0.03
SPL	163.79	0.00 **	0.10	142.83	0.00 **	0.09
IN * TN	0.37	0.96	0.00	1.36	0.19	0.01
IN * SPL	8.65	0.00 **	0.01	4.94	0.01 *	0.01
TN * SPL	1.78	0.11	0.01	0.40	0.85	0.00
IN * TN * SPL	0.68	0.75	0.01	0.49	0.90	0.00

According to the MANOVA analysis, the influential factors of acoustic comfort and noise disturbance are the same. There was a strong negative correlation between acoustic comfort and noise disturbance (r = −0.7, $p < 0.001$). To reduce the repetitive results, only results related to acoustic comfort are presented in the following sections.

According to the size factor (η_p^2), traffic noise level (SPL) was found to be the most influential factor, followed by the interior noise type (IN), and the traffic noise type (TN). This result indicates that controlling the noise level is the most efficient measure to reduce the negative impact of combined noises. As for the noise sources, participants were more affected by the interior noise source than the exterior traffic noise source.

3.1. Effect of Traffic Noise on Sound Environment Evaluations

According to the results from the MANOVA analysis, both the traffic noise source and the traffic noise level exerted significant influences on sound environment evaluations. Figure 8 shows the relationship between traffic noise sources and acoustic comfort evaluations. A pairwise comparison was conducted to identify significant differences among noise groups.

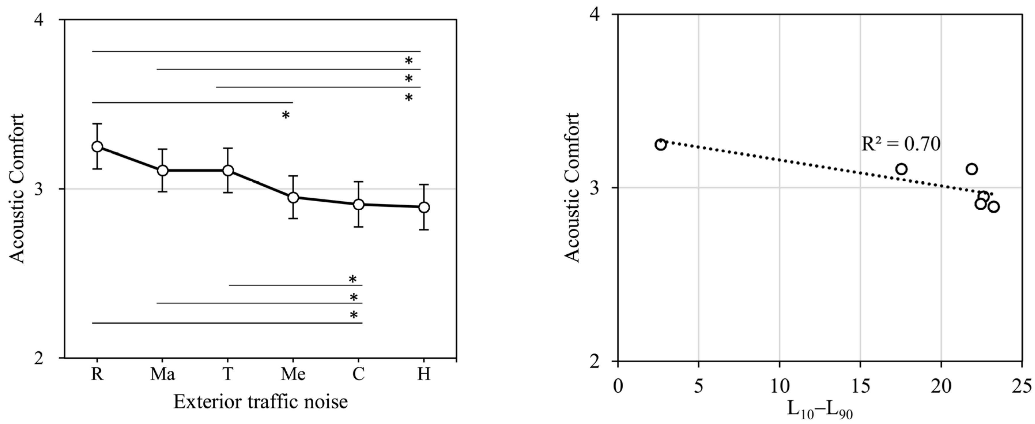

Figure 8. Effect of traffic noise source and traffic noise level on sound environment evaluations. The symbol '*' represents a significant difference at the 0.05 significance level in the pairwise comparison analysis (LSD method).

First, there were significant differences between road traffic noise (R) and three rail traffic noises. Acoustic comfort evaluations with respect to R were significantly higher than those relative to Me, C, and H. However, the differences between R and the other two rail traffic noises (Ma and T) were found to be insignificant. Meanwhile, there were significant differences among rail traffic noises. The evaluations of maglev and tram noises were significantly higher than those relative to conventional train and high-speed train noise.

These differences caused by traffic noise sources can be explained by variations in the temporal fluctuation characteristics of the noises. The order of traffic noise sources in Figure 8 is a reflection of the order of the noise temporal fluctuations (L_{10}–L_{90}) shown in Table 1 (R < Ma < T < Me < C < H). Therefore, the results in Figure 8 show that, as the temporal fluctuation (L_{10}–L_{90}) increased, the impact of traffic noise on people's perception of the sound environment also increased. This resulted in lower acoustic comfort and higher noise disturbance. It was found that acoustic comfort was highly correlated with L_{10}–L_{90} (R^2 = 0.7), as shown in Figure 8.

Figure 9 shows the effect of traffic noise levels on subjective evaluations. With the traffic noise level increasing from 40 dB to 50 dB, the acoustic comfort improved, and noise disturbance decreased significantly across all traffic noise groups. This is consistent with the results from the MANOVA analysis that show that SPL was the most influential factor for subjective evaluations.

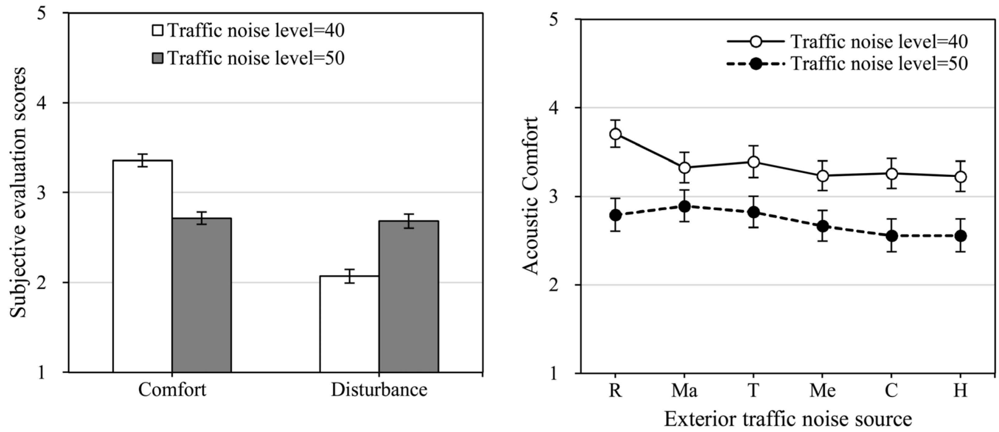

Figure 9. Effect of traffic noise level on sound environment evaluations in different traffic noise groups.

It was also found that the differences in acoustic comfort caused by SPL changes vary among different traffic noise groups. For road traffic noise, the mean acoustic comfort rating was improved from 2.79 (neither comfortable nor uncomfortable) to 3.71 (comfortable) by decreasing the traffic noise level by 10 dB. On the other hand, the effects of a 10 dB SPL decrease on acoustic comfort evaluations in the rail traffic groups were relatively small (Ma: 0.43; T: 0.57; Me: 0.57; C: 0.7; H: 0.67).

To quantify the effect of SPL changes on subjective evaluations, the differences in acoustic comfort as the noise level increased from 40 dB to 50 dB ($Comfort_{40}$–$Comfort_{50}$) were calculated, as shown in Figure 10. For each noise combination configuration, such as the combination of air-conditioner noise and high-speed train noise, the difference in acoustic comfort ratings between the 40 dB stimulus and the 50 dB stimulus was calculated. Therefore, the positive values of $Comfort_{40}$–$Comfort_{50}$ in Figure 10 indicate that people felt less comfortable as SPL increased. A higher value in $Comfort_{40}$–$Comfort_{50}$ indicates that the SPL change of this noise source had a more significant influence on people's evaluations.

The results from the ANOVA analysis show that the $Comfort_{40}$–$Comfort_{50}$ was significantly higher in the road traffic group compared to the four rail traffic groups (Ma, T, Me, and H). This fact reveals that the participants were more sensitive to the noise level when exposed to road traffic noise than to rail traffic noise. Among the rail traffic groups, the $Comfort_{40}$–$Comfort_{50}$ increased with the temporal fluctuation (L_{10}–L_{90}). The results indicate that participants were more sensitive to the noise level of sounds that fluctuate more. There was a significant difference between Ma and C in the pairwise comparison.

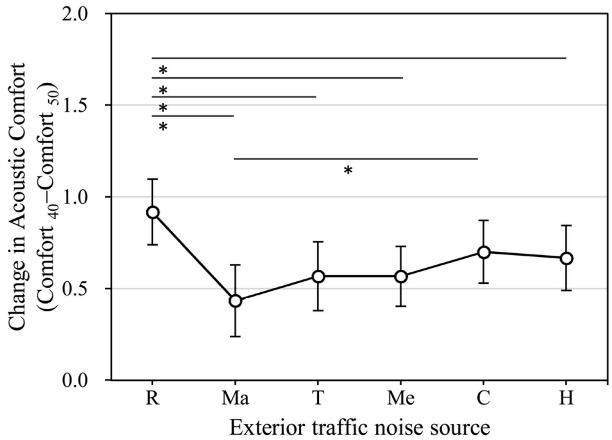

Figure 10. Effect of traffic noise level change on the change in sound environment evaluations in various traffic noise groups. $Comfort_{40}$–$Comfort_{50}$ is the difference in acoustic comfort between the 40 dB group and the 50 dB group. The symbol '*' represents a significant difference at the 0.05 significance level in the pairwise comparison analysis (LSD method).

3.2. Effect of Interior Sound in Combined Noise on Sound Environment Evaluation

Figure 11 shows the main effect of interior noise (IN) on acoustic comfort. The results show that the evaluations in the IS (irrelevant speech) group were significantly worse than those in the SL (silence) and AC (air-conditioner noise) groups. Meanwhile, there were no significant differences between the SL and AC groups.

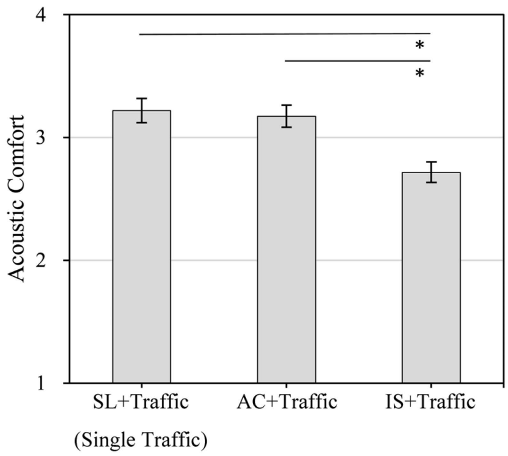

Figure 11. Effect of traffic noise level on sound environment evaluations. The symbol '*' represents a significant difference at the 0.05 significance level in the pairwise comparison analysis (LSD method).

This result reveals that sound environment evaluations are affected by both exterior and interior noise in combined noises. Compared to the SL group (single traffic noise group), the combined noise groups may not necessarily have a stronger impact on people's perception of the sound environment, even as the overall noise level increases. The combination of speech noise and traffic noise was found to have a significantly stronger impact than single traffic noise. On the contrary, no significant differences were found between the SL group and the AC group. This result indicates that adding air-conditioner noise to traffic noise will not significantly affect acoustic comfort, even though the overall noise level increases.

Figure 12 shows the effects of interior noise (IN) on acoustic comfort in different traffic noise source groups. The results for all rail traffic groups are similar. There were two significant differences caused by the interior sound conditions: one between IS and SL, and the other between IS and AC. However, there was only one significant difference in the road traffic group, namely between IS and SL. The differences caused by interior noise conditions were found to be smaller in the road traffic group than in the rail traffic groups. This finding indicates that the interior noise condition has a relatively weaker influence on the combined noise with road traffic noise compared to rail traffic noise.

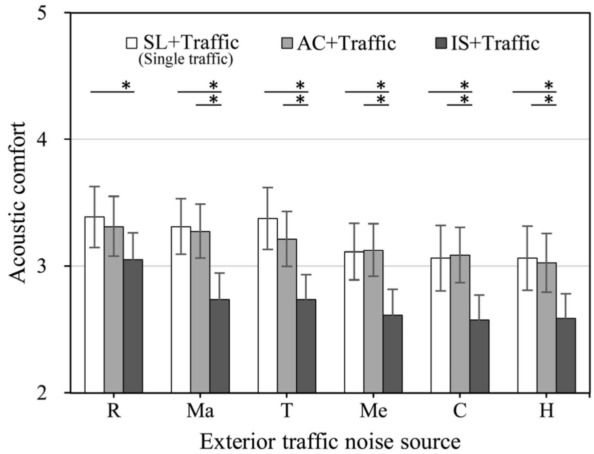

Figure 12. Effect of interior noise condition on sound environment evaluations in different traffic noise source groups. The symbol '*' represents a significant difference at the 0.05 significance level in the pairwise comparison analysis (LSD method).

Figure 13 shows the effect of interior noise (IN) on acoustic comfort across traffic noise level groups. It was found that the effect of interior noise decreased as the traffic noise level increased. As shown in Figure 13 (left image), as the traffic noise level increased from 40 dB to 50 dB, the difference between the SL group and the IS group decreased from 0.25 to 0.75.

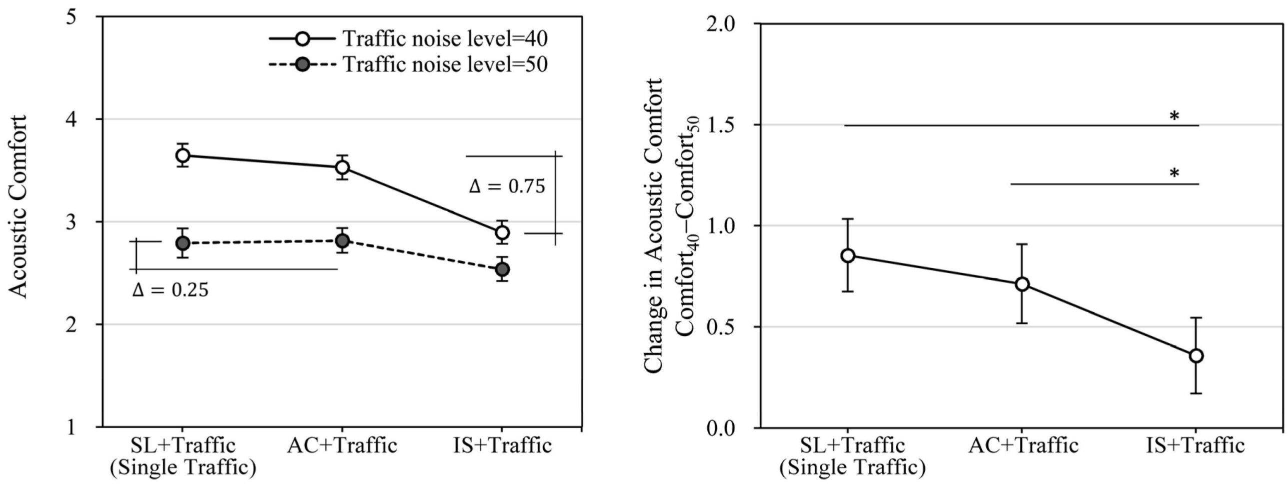

Figure 13. Effect of the interior noise condition on sound environment evaluations in different traffic noise level groups. The symbol '*' represents a significant difference at the 0.05 significance level in the pairwise comparison analysis (LSD method). Δ represents the difference between the SL groups and the IS groups.

On the other hand, the figure also shows that the effect of traffic noise level was dependent on the interior noise source. As shown in Figure 13 (right image), the Comfort_{40}–Comfort_{50} was significantly smaller in the IS group compared to the SL and AC groups. This result shows that people were less sensitive to the traffic noise level when there were interior speech noises in the office room. In quiet offices and offices with air-conditioner noise, people were more likely to be affected by changes in external traffic noise.

4. Discussion

One of the main findings from this study is that there were significant differences in sound environment evaluations due to traffic noise sources which were determined by the temporal characteristics of the noises in question. Most existing studies concur that rail traffic noise has a greater impact than road traffic noise. Through a field survey in residential areas, Brink et al. [44] found that railway noise elicited higher annoyance than road traffic noise at the same L_{den} level. As for the comparison of different rail traffic noises, Di et al. reported similar results. They found that the noise annoyance caused by conventional train noise was significantly lower than that associated with high-speed train noises [45]. In our experiment, we examined up to six different traffic noises. A strong correlation was found between temporal fluctuation characteristics (L_{10}–L_{90}) and the evaluations of the sound environment.

Considering the interior noise, the impact of speech noise was found to be negative, while the air-conditioner noise was neutral when combined with traffic noises. Meanwhile, the difference between these two interior sounds was more significant when combined with more fluctuating traffic sounds. A reasonable explanation for this phenomenon is temporal differences. According to the model proposed by Bert et al. [46], the perception of environmental noise is primarily determined by noticeable events. The speech noise exhibited more temporal fluctuations and more sound events relative to other noise stimuli. As a result, speech noise had a greater negative impact on people. When speech noise was combined with continuous road traffic noise, the background sound level (L_{90}) increased, making noise events less noticeable. Therefore, the distinctions between speech noise and air-conditioner noise were more pronounced in the rail traffic groups than in the road traffic group. In a laboratory experiment, continuous industrial noise was found to have interaction effects with traffic noises due to the change in the temporal evolution of their combined noise [31]. On the other hand, the air-conditioner noise had more sound energy in low-frequency bands compared to the speech noise. Numerous studies have revealed that low-frequency sounds have a stronger masking effect than high-frequency sounds [47]. Meanwhile, a field study found that masking sounds were more efficient at masking fluctuating noises [48].

This study has some limitations. Firstly, there were no control groups in this study. As a result, hearing fatigue might have played a role. In addition, there was only one sound clip for each sound source in this study due to the limitation of the experiment duration. As a result, the reasons for the phenomenon in the experiment could not be verified. For example, significant differences were observed between the speech noise and the air-conditioner noise in the experiment. However, these two noises differ not only in temporal characteristics, but also in spectral characteristics. Further research is needed to confirm the factor responsible for this phenomenon by using multiple stimuli for the same noise source.

5. Conclusions

A laboratory experiment was conducted in this study, focusing on how traffic noise affects individuals in offices subject to different interior sound conditions. The following results were obtained:

a. Both exterior and interior noises were found to influence sound environment evaluations in the experiment. The traffic noise level was found to be the most influential factor determining acoustic comfort and noise disturbance, followed by the interior noise source and the exterior traffic noise source.
b. Significant differences in sound environment evaluations were observed among various traffic noise groups. The results indicate that the temporal fluctuation character-

istic (L_{10}–L_{90}) was a crucial factor in determining the valence of evaluations of the sound environment. The results reveal that the adverse effects of rail traffic noises were more significant than those of road traffic noise. Meanwhile, the participants were more sensitive to the traffic noise level in the road traffic noise group than in the rail traffic group. Among the rail traffic groups, participants were more sensitive to the traffic noise level when exposed to traffic noises that temporally fluctuated compared to steady noises.

c. Interior sounds also had significant influences on sound environment evaluations when combined with traffic noises. The irrelevant speech noise was found to have a negative effect, while the air-conditioner noise had a neutral effect when combined with traffic noises. The impact of interior sounds was more pronounced when combined with railway noise compared to road traffic noise. Meanwhile, the results also show that the participants were more sensitive to the traffic noise level when there was air-conditioner noise rather than speech noise.

The current exploratory study presents the results of a laboratory experiment that focused on the effect of exterior traffic noises on the acoustic environment of office spaces characterized by varying interior noise conditions. The results demonstrate that both interior and exterior traffic noises influenced how people perceived the combined noise. As for the exterior traffic noises, the results reveal that the noise insulation was most efficient in reducing the impact of traffic noises in the office spaces, regardless of the interior noise condition. Meanwhile, the effect of traffic noise sources should be considered when evaluating the impact of traffic noise. As for the interior design of the office environment, the results of this study indicate that the effect of noise control treatments differs based on the noise source. In open-plan offices, controlling speech noise could probably improve the employee's perception of the acoustic environment. In enclosed offices without speech noises, the noise control treatments might be less effective. In general, the impact of combined noises was affected by various factors and could not be adequately explained by the overall sound level. In future studies, we will focus on examining the effect of temporal and frequency characteristics on subjective evaluations. Such an approach could lead to the development of practical tools for architects, planners, and city managers to estimate not only the impact of combined noises in office environments, but also the effectiveness of noise treatments.

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