The influence of crowd density on the sound environment in commercial pedestrian streets

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Abstract

Commercial pedestrian streets are typically historic or cultural centres in cities, and their environment, which includes the sound environment, is notably important. The objective of this study is to explore the relationships between crowd density and evaluation of the sound environment in commercial pedestrian streets. At the case study site in Harbin, China, on-site measurements were performed, and a questionnaire survey was carried out. The analysis of the sound pressure level showed that when the crowd density is less than 0.05 persons/m^2, the effect on the sound pressure level is insignificant, whereas when the crowd density is greater than 0.05 persons/m^2, the sound pressure level increases with crowd density. The analysis of sound sources showed that several typical sound sources, such as traffic noise, can be masked by sounds due to the crowd density. The analysis of the acoustics showed that when the crowd density is less than or greater than a certain value, e.g., 0.10 to 0.25 persons/m^2, the acoustic comfort evaluation score decreases with a lower or higher crowd density. In terms of audiovisual characteristics, the subjective loudness can increase with a greater crowd density, whereas the acoustic comfort can decrease. Results for an indoor underground shopping street are also presented for comparison.

Keywords: Crowd density; commercial pedestrian street; subjective loudness; acoustic comfort; audiovisual interaction

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1. Introduction

As typical urban open spaces, commercial pedestrian streets, which are often historic or cultural centres in cities, are common in China. Despite many studies on how to enhance the comfort and safety of commercial pedestrian streets in the last several years (Foltˆete and Piombini, 2007; Leng and Sun, 2009), the 2011 environmental bulletin of China cited environmental problems, particularly acoustic problems, as still being major detrimental factors in the use and evaluation of commercial pedestrian streets by users (Ministry of Environmental Protection of the People's Republic of China, MEPPRC, 2011).

Previous studies have suggested that the evaluation of the sound environment of an urban open space depends strongly on the different sound sources, specific characteristics of the space, various physical environmental conditions, and users' social and behavioural characteristics (Ballas, 1993; Gaver, 1993; Maffiolo et al., 1997; Dubois, 2000; Ge and Hokao, 2004 and 2005, Kang and Zhang, 2010). For sound factors, it has been demonstrated that for sounds with multiple tonal components, the perceptual process is different from that of single tonal component because the attention of subjects is not automatically focused (Bodden and Heinrichs, 2001). Several special sound sources can also be evaluated higher by users, even if the sound level is generally low(Farina et al., 2011; Nilsson, 2010; Jeon et al., 2012;). In terms of spatial characteristics, Kang (2001) indicated that a suitable reverberation time, e.g., 1–2 s, can make street music more enjoyable. In terms of environmental characteristics, the importance of temperature and humidity in the environment in evaluating the acoustics has been demonstrated (Yang and Kang, 2005, Yu, 2009). Regarding user characteristics, the results primarily focus on individual differences, such as gender, age, income, occupation, education, and their behavioural characteristics (Zimer and Ellermeier, 1999; Karlsson, 2000; Ellermeier et al., 2001; Crociata et al. 2012 and 2013). whereas there have only been a limited number of studies regarding the influence of crowd distribution on the sound environment.

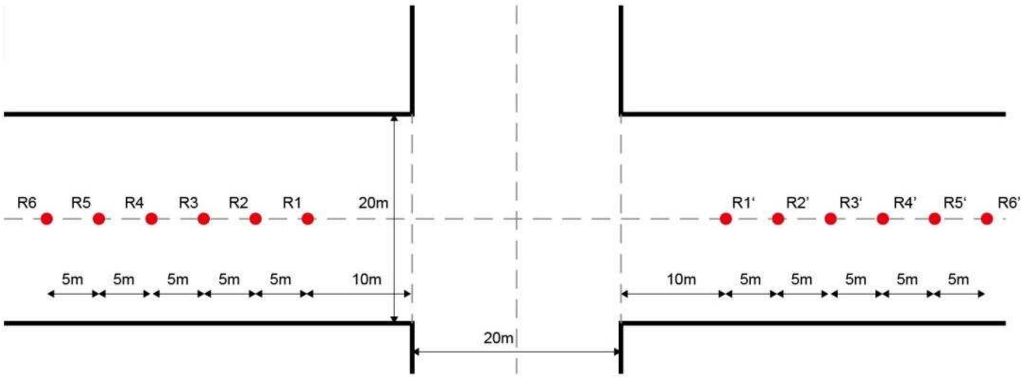
Therefore, the present study examines the influence of crowd density on the sound environment with objective characteristics, i.e., sound pressure level and sound sources, and subjective characteristics, i.e., evaluation of acoustics and audiovisual interaction, based on measurements and a series of subjective surveys in a typical commercial pedestrian street. For comparison, results of an indoor underground shopping street are also presented.

2. Methodology

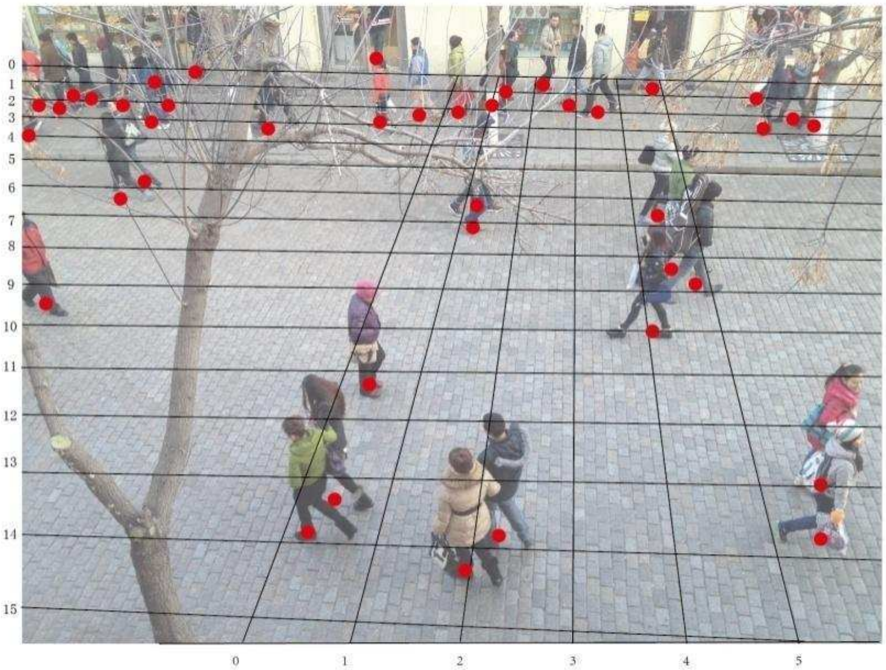
2.1. Survey site

In China, commercial pedestrian streets are nearly in every city centre. Most of these streets are traditional streets, and therefore, the building heights on both sides of these streets are generally low, e.g., 2 to 4 floors (8 to 16 m in height), and the aspect ratio of the street cross-section typically ranges from 1:1 to 1:3 (Guo, 2010). These types of streets are rather similar to many streets in Europe (Ashihara, 1983).

In the present study, a traditional commercial pedestrian street, the Central Avenue in Harbin, China, was chosen as the case site. It is a historic and cultural centre, built in 1898 by the Russians, and the buildings on both sides of the streets are of 3 to 4 floors. The street is 1450 m in length and 20 m wide. Because traffic noise is typically the primary source of noise in urban open spaces (Miedema and Vos, 1998; Lebiedowska, 2005), survey locations were selected from a section on this street with a traffic road, which is 20 m wide, as shown in Fig. 1a. The crowd density on one side of the street is high and is low on the other side; therefore, the survey points are along both sides of the street and are denoted R1 to R6 on the generally high crowd density side and R1' to R6' on the generally low crowd density side. The spacing between survey points is 5 m. R1 and R1' are 10 m away from the border of the traffic road to ensure that the pedestrians' behaviour is generally the same (Yu and Kang, 2009).



(a)



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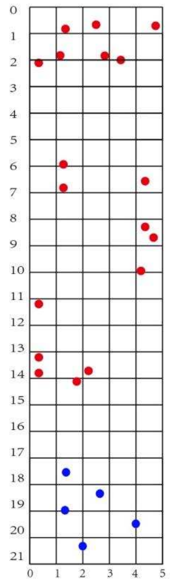

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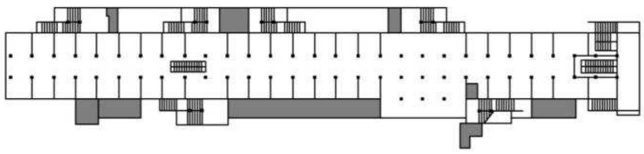


(d)

Figure 1. The survey site and the measurement points along the commercial pedestrian street (a), photograph of the crowd density at point R2 (b), measurement of crowd density at point R2 (c), schematic of the underground shopping street (d)

2.2. Questionnaire survey

To study the influence of crowd density on the acoustic characteristics, including the subjective loudness and acoustic comfort, a questionnaire survey was carried out, simultaneously with the crowd density measurements, and every questionnaire was generally completed in 3-4 minutes. In total 662 valid questionnaires were obtained. Approximately 20 to 30 interviews were conducted at each survey point. The interviewees in all the field surveys were randomly selected, and their educational and social backgrounds and their on-site behaviours were shown to be representative (Yu and Kang, 2010). The surveys were conducted at various times from morning to evening, which were divided into three periods: 09:00 to 11:59, 12:00 to 14:59, and 15:00 to 18:00. A five-point bipolar category scale was used in the questionnaire design. Subjective loudness was evaluated with five levels: 1, very quiet; 2, quiet; 3, neither quiet nor noisy; 4, noisy; and 5, very noisy. Acoustic comfort was evaluated with five levels: 1, very uncomfortable; 2, uncomfortable; 3, neither comfortable nor uncomfortable; 4, comfortable; and 5, very comfortable. Before the formal investigation was conducted, the reliability and validity of the questionnaire were tested for suitability of the final questionnaire (Raimbault, 2006). Considering that interviewees were required to be in the sound environment for a period of time to properly evaluate the spaces (Kang, 2004), users who were in the commercial pedestrian street for less than half an hour were not interviewed. The surveys were conducted every 10 minutes at the survey locations to ensure stochastic behaviour in the survey (Yang and Kang, 2005).

2.3. Crowd density measurement

The crowd density was measured at every survey point in an area of 5 m*20 m, and these areas were divided into 1m by 1m grids. Figure 1b shows an example at point R2. The pedestrians can be sorted by these grids. In Fig. 1c, the locations of pedestrians are marked that can be used for further statistical analysis. The red dots denote pedestrians in the photographs, whereas the blue dots denote pedestrians who were not in the photographs, which is because, the photographs were taken on a balcony and several pedestrians under the balcony were missed but marked by another person while the photographs were taken. The crowd density for every survey point is shown as the average number of persons per square meter (persons/m^2) in 5 minutes.

2.4. Sound level measurement

The sound pressure level was measured immediately following each interview. For each measurement, the microphone of the sound level meter was positioned approximately 1 m away from any reflective surfaces and 1.2 m to 1.5 m above the ground to reduce the effect of acoustic reflection (Kang 2006). This measurement method was also used to measure the indoor sound pressure level in previous studies (Chen et al., 1991; Pettersson, 1997; Walerian et al., 2001). The sound level meter was set in slow-mode and A-weight, and a reading was taken every 3 s to 5 s. A total of 5 minutes of data were obtained at each survey position, and the corresponding LAeq was derived. Simultaneously, several other environment factors, e.g., air temperature, relative humidity, and luminance, were also measured, although they are not analysed in this paper.

2.5. Consideration of other factors

For the sake of examining the differences between indoor and open spaces, an underground shopping street, as shown in Figure 1d, was also selected. The same questionnaire survey and same measurements of crowd density and environment factors were also performed for this street (Meng et al, 2013; Meng and Kang, 2013).

In terms of the audiovisual interaction, two videos were taken during the investigations where photographs of the crowd density were taken: one with a higher crowd density of 0.28 persons/m^2, and the other at a lower crowd density of 0.08 persons/m^2. Two audios were also taken during the investigation at the location where the sound pressure level was measured, one at a higher sound pressure level of 76 dBA, and the other at a lower sound pressure level of 69 dBA. For each video the sound pressure level variation was within about 3 dBA, which was rather stable(Kang et al, 2012).

2.6. Statistical analysis

The results were analysed with SPSS Software 15.0 (Yin and Liu, 2008) using linear and nonlinear correlations from regression analysis, Pearson/Spearman correlations (two-tailed), and mean differences (t-test, two-tailed) for factors with two scales.

3. Results and analysis

Based on the survey and the measurement results, this section presents the effect of crowd density on the sound environment by considering both objective characteristics, e.g., sound pressure level and sound sources, and subjective characteristics, e.g., evaluation of acoustic comfort and subjective loudness, as well as audiovisual interactions.

3.1. Influence of sound pressure level

The relationships between crowd density and the measured LAeq are shown in Figure 2a, where linear regressions and the coefficient of determination R^2 are also presented. Figure 2a shows that there is a general correlation between the crowd density and the measured sound level ($p<0.001$), although the coefficient of determination R^2 was only 0.261 (dotted line) when the crowd density ranged from 0 to 0.40 persons/m^2. To evaluate this trend, at a scale of 0.02 persons/m^2, the mean crowd density with the mean LAeq is also presented in Figure 2a using the solid block. It can be observed that the influence of crowd density exhibited a positive, linear trend with an R^2 value of 0.724, and there was also a positive correlation with an R^2 value of 0.401 (solid line) when the crowd density was greater than 0.05 persons/m^2. It is interesting to note that the relationships between the crowd density, when it was less than 0.05 persons/m^2, and the measured LAeq are not significant based on a significance level defined as $p>0.1$. A possible reason is that sound level is primarily influenced by other sound sources, e.g., a PA system or traffic noise, when the crowd density is generally less than 0.05 persons/m^2.

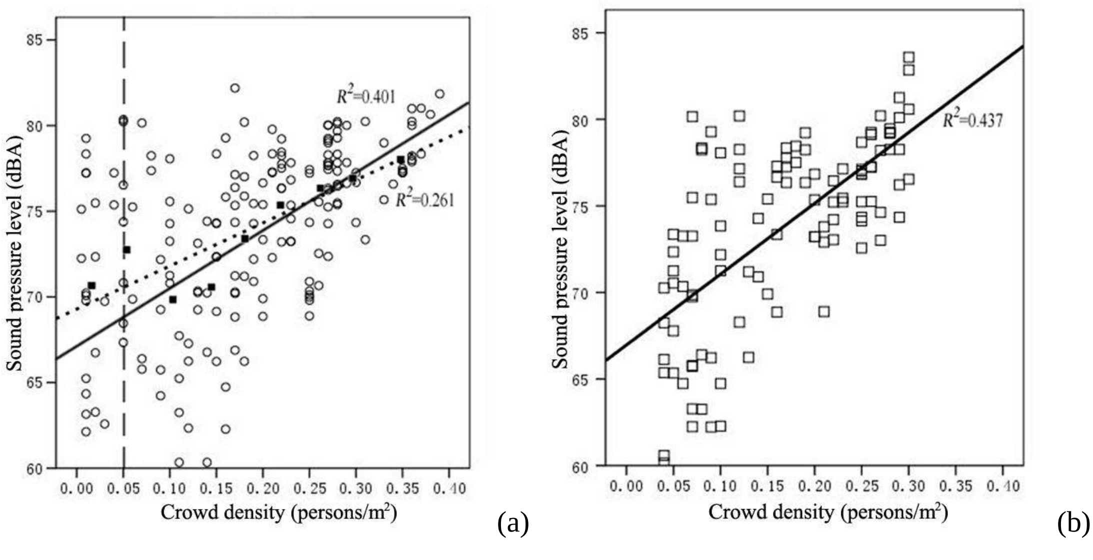


Figure 2. Influence of crowd density on the measured sound pressure level on the commercial pedestrian street (a) and the influence of crowd density on the measured sound pressure level on the underground shopping street (b)

It is interesting to note that the relationship between the crowd density and the measured LAeq is also linear for the underground shopping street, with a coefficient of determination R^2 of 0.437.

A model was also created to calculate the influence of crowd density on sound pressure level, where 2-256 people were randomly arranged in an open area of 20 m*20 m, where the receiver R was located in the middle of the area. All the people were more than 3 m away from the receiver R to avoid any bias by single individuals (Kang, 2006). Figure 3(a) presents an example of the model with 128 people. For the sake of convenience, reflections from the ground and walls were not considered in this model, and in the calculation, the sound power level of every person was fixed at 60 dBA (Zhang, 2008).

The sound pressure level for one person at receiver R is calculated by

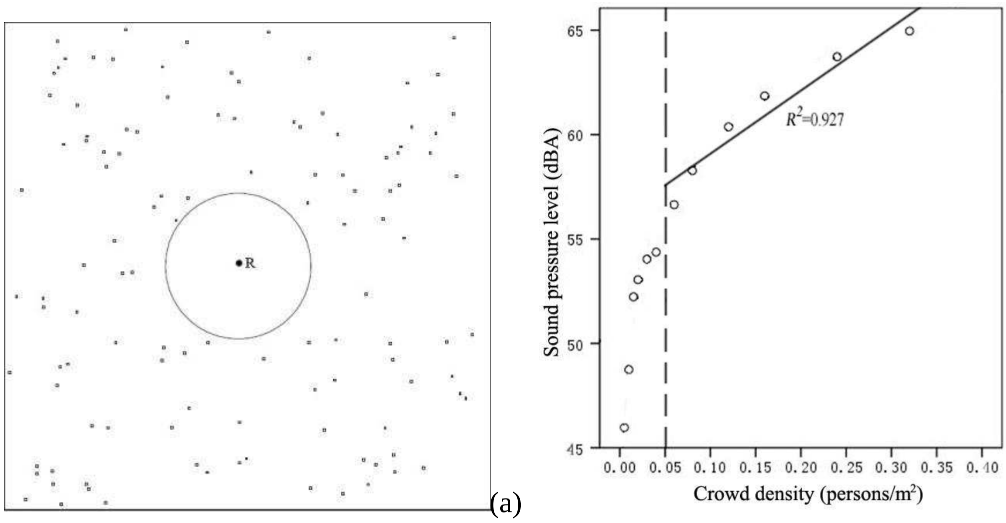
$$L_p = L_w - 10\lg\frac{1}{4\pi r^2} \qquad (1)$$

where L_p is the sound pressure level, L_w is the sound power level, and r is the distance between the person and receiver R.

The sound pressure level for all persons at receiver R is calculated by

$$L_p = 10\lg\left(10^{\frac{L_{p_1}}{10}} + 10^{\frac{L_{p_2}}{10}} + \cdots + 10^{\frac{L_{p_n}}{10}}\right) \qquad (2)$$

The relationships between the crowd density and the calculated LAeq are shown in Figure 3b, in which linear regressions and the coefficient of determination R^2 are also presented. It is interesting to note that when the crowd density is greater than 0.05, the slope ratios of the regression equation for the measurement and calculation are nearly the same, where the regression equations are y=33.74x+67.12 (measurement) and y=30.68x+55.96 (calculation). This result confirms that the sound pressure level can generally be altered by crowd density with or without other sound sources.



(a) (b)

Figure 3. A model used to simulate the influence of crowd density on sound pressure level on the commercial pedestrian street with 128 points in the area (a) and the calculation results (b)

3.2. Influence of sound sources

The interviewees were asked to describe up to five sounds they heard in the commercial pedestrian street during the interview and to note the three sounds they heard first (Semidry, 2006). In this section, the percentages of hearing the typical sound sources with different crowd densities are analysed.

3.2.1. Influence of traffic noise

A statistical analysis of the survey results showed that traffic noise was most cited by users, with a frequency of 526 times. The percentage of users who heard traffic noise at different crowd densities is shown in Figure 4, where G1 indicates the data for R1 to R3 and R1' to R3', which represent the area near the traffic road, and G2 indicates the data for R4 to R6 and R4' to R6', which represent the area far away from the traffic road.

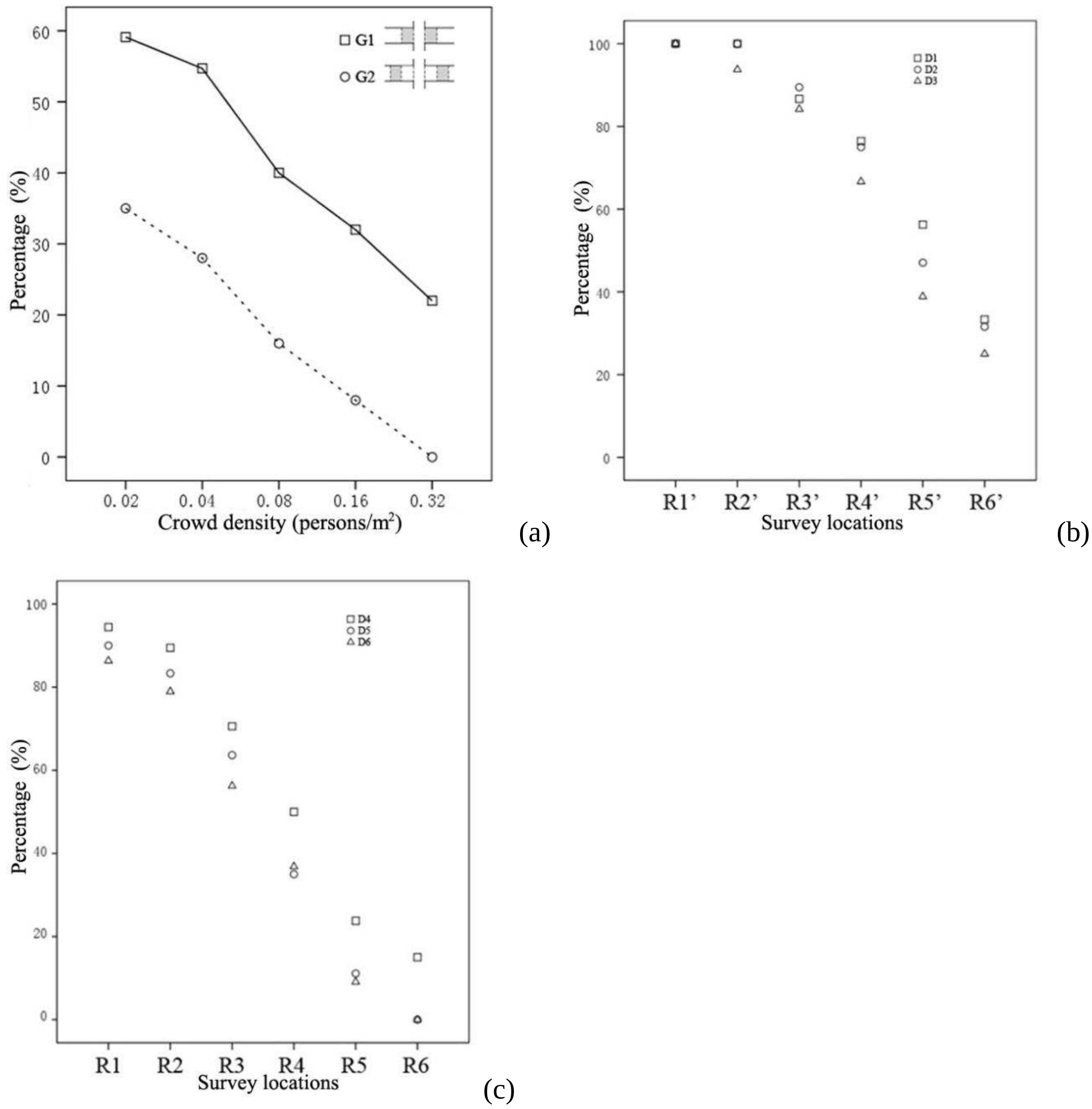


Figure 4. The percentage of users who heard traffic noise at different crowd densities (a), where G1 represents the data for R1 to R3 and R1' to R3', G2 represents the data for R4 to R6 and R4' to R6', the percentage of users who heard traffic noise at R1 to R6 (b) and R1' to R6' (c)

Figure 4a shows that the percentage of users hearing traffic noise ranged from 59% to 22% when users were near (<20 m) the traffic road, whereas the percentage ranged from 35% to 0%

when users were far (25 to 35 m) from the traffic road for crowed densities ranging from 0.02 to 0.32. The users near the traffic road heard more traffic noise than users who were far from the traffic road, regardless of the crowd density, with a mean difference of 24% ($p<0.01$). Traffic noise can be masked by crowd density: when the crowd density doubled, the percentage of users who heard traffic noise generally decreased to 7%. Compared with crowd density, distance was more effective in reducing the traffic noise that was heard.

Further analysis of the influence of crowd density on traffic noise was conducted, the results of which are shown in Figures 4b to 4e, where R1-R6 were located in an area of relatively low crowd density area, e.g., a crowd density ranging from 0.01 to 0.06 persons/m^2, whereas R1'-R6' were located in an area of relatively high crowd density, e.g., a crowd density ranging from 0.16 to 0.31 persons/m^2. In this section, Dn denotes these particular crowd densities, where D1=0.01, D2=0.03, D3=0.06, D4=0.16, D5=0.23, and D6=0.31 persons/m^2.

As shown in Figures 4b and 4c, all users at R1' and R2' and most of the users at R1 and R2 could hear traffic noise when the crowd densities were D1 and D2. This result demonstrates that when a user is generally within 15 m from a traffic road, crowd density cannot mask traffic noise. When the users were at R3'-R6', the traffic noise they heard decreased to 66% (D1), 69% (D2), and 69% (D3), respectively. This result indicates that when the crowd density is relatively low, the effect of distance in masking traffic noise does not vary and decreases by an average of 3.5% traffic noise per meter. When the users were at R3 and R6, the traffic noise they heard decreased to 75% (D4) and 83% (D5), respectively. This result indicates that when the crowd density is relatively high, the effect of distance in masking traffic noise is enhanced. It should be noted that the percentage of users who heard traffic noise was 0% at R6, and therefore, the distance from R2 to R5 was used, for which the percentage of users who heard traffic noise decreased to 77%. The effect of distance in masking traffic noise was generally 4% per meter on average when the crowd density was relatively high.

3.2.2. Influence of other sound sources

In addition to traffic noise, there were three other sound sources that were also generally cited by users (>300 times): PA systems (482 times), music from shops (325 times), and surrounding conversations (318 times). Therefore, the influence of crowd density on these three sound sources were also investigated, with the results presented in Figure 5, where G1 indicates the data for R1-R3 and R1'-R3' and represents the area near the traffic road and G2 indicates the data for R4-R6 and R4'-R6' and represents the area far from the traffic road.

It is interesting to note from Figure 5a that the percentage of users who heard a PA system generally decreased from 19% to 37% when users were near the traffic road, whereas the figure generally increased from 52% to 32% when users were far from the traffic road when the crowed density ranged from 0.02 to 0.32. A rather different trend was thus observed when users heard a PA system at different crowd densities. One possible reason why this result was obtained is that when users were near the traffic road, the large crowd density could mask part of the traffic noise, which was the primary sound source, and therefore, users heard more of the PA system. When users were far from the traffic road, the greater crowd density may have allowed users to pay attention to other sound sources, such as surrounding conversations and footsteps. Subsequently, their focus on the PA system may have been decreased.

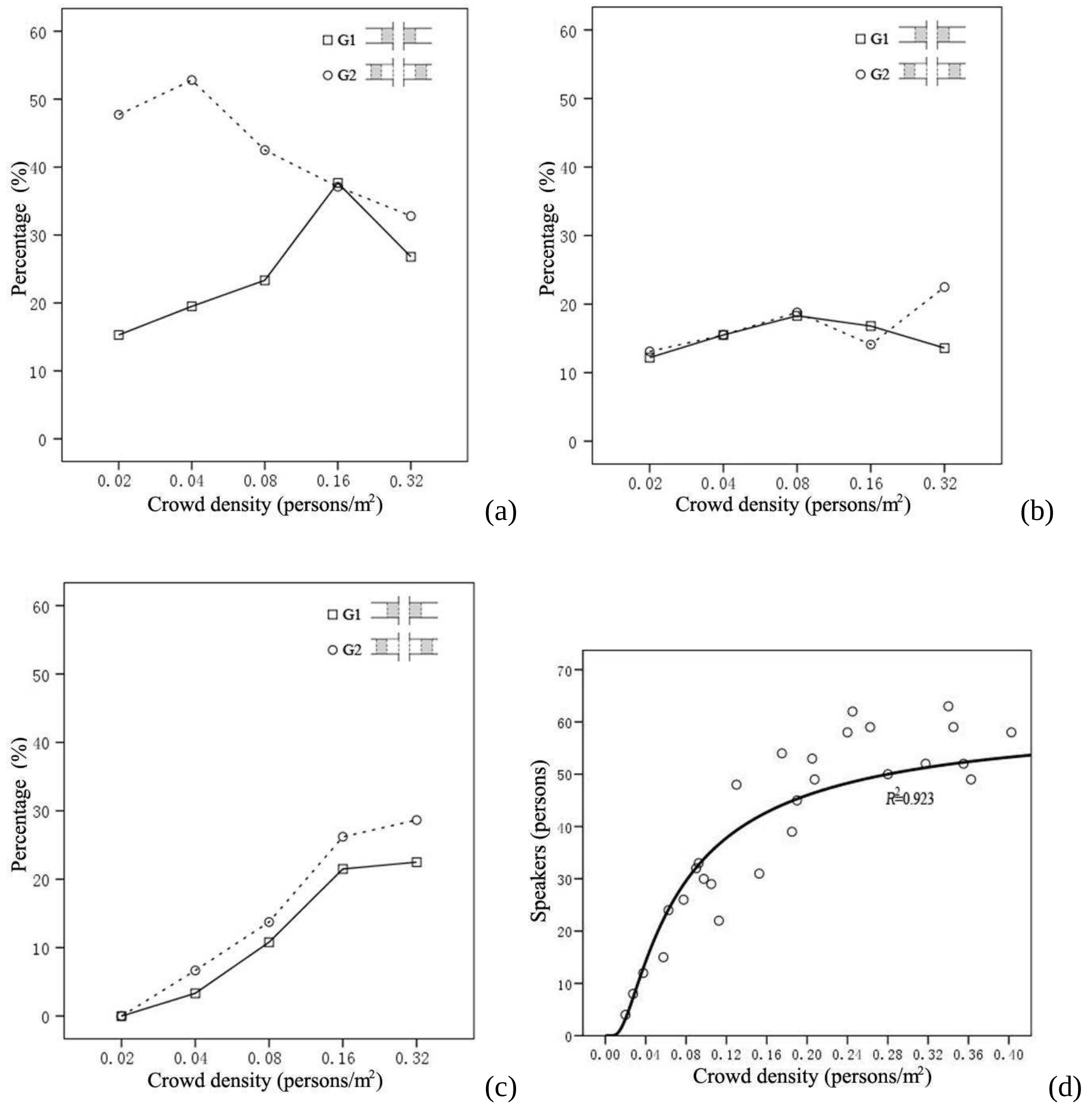


Figure 5. Percentage of users who heard other sound sources at different crowd densities, where G1 represents the data for R1 to R3 and R1' to R3', G2 represents the data for R4 to R6 and R4' to R6' for a PA system (a), music from shops (b), surrounding conversations (c), and the influence of crowd density on number of speakers (d)

With respect to music from shops, as shown in Figure 5b, hearing preference did not vary appreciably, ranging from 12% to 18% when users were near the traffic road, whereas hearing preference ranged from 13% to 22% when users were far from the traffic road when the crowed density ranged from 0.02 to 0.32. There are two reasons that may explain why hearing music from shops did not change. One is that sound sources are generally directional, and therefore, other sound sources cannot mask them effectively. The other is that music from shops typically has linguistic meaning and therefore can more easily attract attention from users compared with other sound sources lacking such meaning.

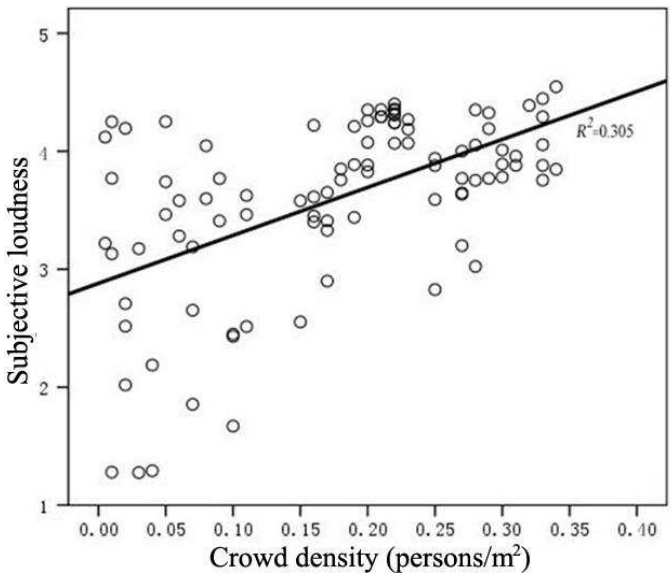
As shown in Figure 5c, the percentage of noise heard from surrounding conversations ranged from 0 to 23% when users were near the traffic road, whereas the percentage ranged from 0 to 29% when users were far from the traffic road when the crowd density ranged from 0.02 to 0.32. When the crowd density was extremely low, i.e., 0.02 persons/m^2, surrounding speech was completely masked by other sound sources. The percentage of noise heard from surrounding speech grew rapidly, i.e., from 3% to 22% in G1 and 7% to 26% in G2, when the crowd density ranged from 0.04 persons/m^2 to 0.16 persons/m^2. On the other hand, the percentage of noise heard from surrounding conversation increased slowly, i.e., from 21% to 23% and 26% to 29%, when the crowd density was even higher, from 0.16 persons/m^2 to 0.32 persons/m^2, respectively.

Further investigation was conducted to explain why the noise from surrounding conversations increased slowly when the crowd density was very high. Sixteen volunteers were instructed to record how many people were talking in an area measuring 20 m*20 m in the commercial pedestrian street. Each volunteer stayed within a 5 m*5 m area, and every 15 minutes, the volunteers simultaneously recorded data. The relationship between crowd density and the number of speakers is shown in Figure 5d, where the corresponding regressions and coefficients of determination R^2 are also presented. Figure 5d shows that when the crowd density was relatively high, e.g., greater than 0.16, the number of speakers increased slowly. It can be observed that more people spoke with each other in a low crowd density in the open space.

3.3. Influence of subjective evaluation

The relationships between the measured crowd density and the subjective perception of sound level (1, very quiet; 2, quiet; 3, neither quiet nor noisy; 4, noisy; and 5, very noisy), referred to as subjective loudness below, are shown in Figure 6a, where the corresponding linear regressions and correlation coefficients R^2 are presented. Figure 6a shows that there was generally a strong positive correlation between the crowd density and the subjective loudness ($p<0.001$), with a correlation coefficient of $R^2=0.307$. As the crowd density increased, the mean score of subjective loudness increased. The influence of crowd density on subjective loudness in an underground shopping street is also presented in Figure 6b for comparison, where the corresponding linear regressions and the correlation coefficient R^2 are also presented. Figure 6b shows that there was also a strong positive correlation between the crowd density and the subjective loudness ($p<0.001$), with a correlation coefficient of

R^2=0.551. It should be noted that the effect of crowd density on subjective sound level was generally stronger in the underground shopping street than it was in the commercial pedestrian street, perhaps due to the enclosed feature of the space.



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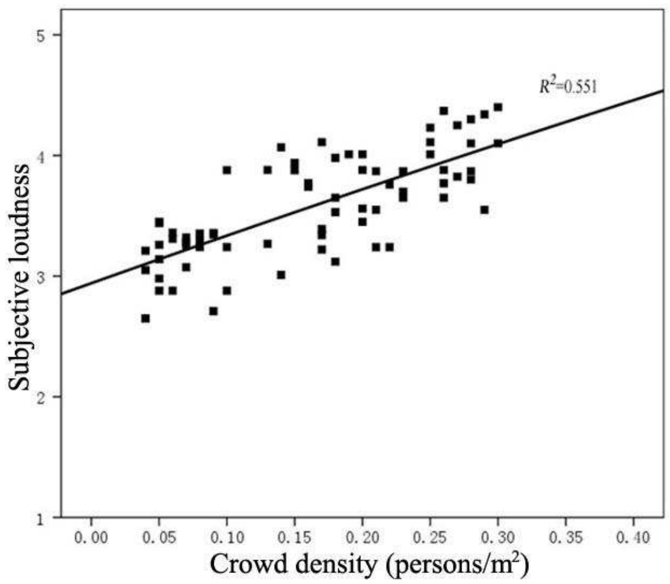


(b)

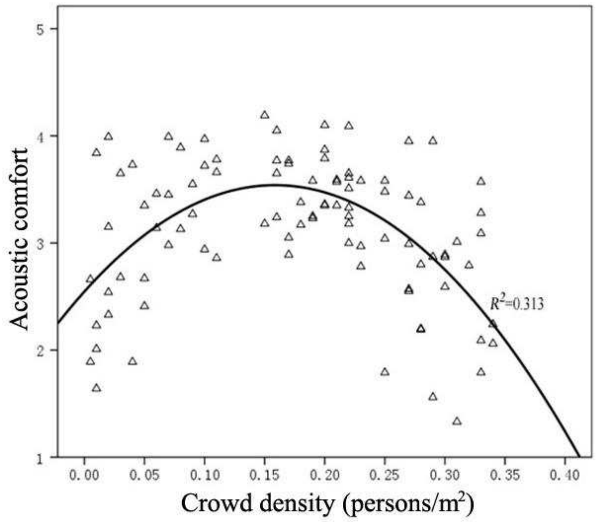
Figure 6. Relationships between crowd density and subjective loudness on the commercial pedestrian street (a) and on the underground shopping street (b)

In Figure 7a, the relationships between crowd density and perceived acoustic comfort level (1, very uncomfortable; 2, uncomfortable; 3, neither comfortable nor uncomfortable; 4, comfortable; and 5, very comfortable) are shown with the corresponding quadratic regressions and correlation coefficients R^2. It can be observed that there was generally a strong correlation between the crowd density and the subjective perception of acoustic comfort ($p<0.001$), with an R^2 value of 0.313. It is interesting that the relationship between the crowd density and perceived acoustic comfort is parabolic. When the crowd density was lower or greater than a certain value, approximately 0.10 to 0.25 persons/m^2, the acoustic comfort score decreased with both decreasing and increasing crowd density. In other words, people felt that the acoustic environment was less comfortable with both a lower and a higher crowd density. A possible reason to explain why acoustic comfort is low when the crowd density is low, is that in a commercial pedestrian street, people appear to prefer a lively environment, as stated by one customer: 'I don't want to shop in dull stores; instead, I would like to be surrounded by noise and lively crowd'. However, if the crowd density becomes relatively high, for example, greater than 0.25 persons/m^2, people will begin to feel acoustically uncomfortable. A further study was performed to test this hypothesis. Sixteen volunteers were invited to perform the same investigation regarding the influence of acoustic comfort as a function of crowd density in a different area located 100 m away from the traffic road and on the same commercial pedestrian street. This distance was far enough such that the traffic noise was not an issue to users (Kang, 2006). The results obtained are shown in Figure 7b, where the relationships between the crowd density and the perceived acoustic comfort level are shown with the corresponding quadratic regressions and correlation coefficients R^2. Figure 7b shows that the relationship between the crowd density and the perceived acoustic comfort level is also parabolic in shape, with an R^2 value of 0.539 ($p<0.001$). This result agrees with the reasoning based on user preference.

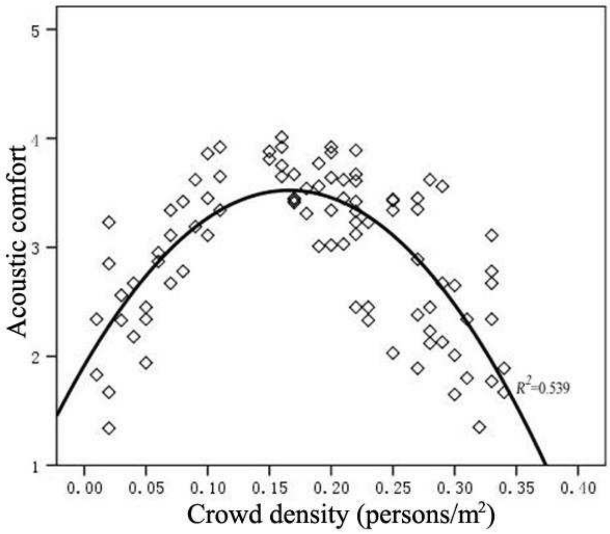
It is interesting that in the underground shopping street, similar parabolic tendencies in acoustic comfort evaluation were also found, as shown in Figure 7c, with an R^2 value of 0.382 ($p<0.001$). It should be noted that in the underground shopping street, users reported a higher level of acoustic comfort at a certain crown density, approximately 0.05 to 0.20 persons/m^2, which is 0.05 persons/m^2 lower than that in the commercial pedestrian street. A possible reason for this finding is that the spatial scale of the underground shopping street is lower than that of the commercial pedestrian street, and therefore, the perception of the same level of acoustic comfort requires a lower crowd density.

3.4. Audiovisual influence

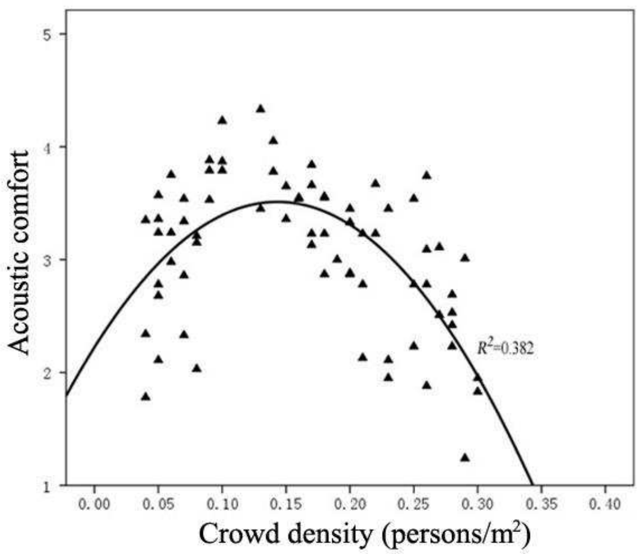
In terms of audiovisual interaction, Southworth (1969) found that attention to visual forms reduces the conscious perception of sound when aural and visual settings are coupled and vice versa. The interaction between auditory and visual perception gives people a sense of involvement, which leads to more comfort, particularly when the auditory perceptions are related to visual components. Therefore, in this study, several experiments concerning the influence of crowd density on audiovisual interactions were also performed.


Acoustic comfort
Crowd density (persons/m²)
R²=0.313
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
1 2 3 4 5

(a)


Acoustic comfort
Crowd density (persons/m²)
R²=0.539
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
1 2 3 4 5

(b)


Acoustic comfort
Crowd density (persons/m²)
R²=0.382
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
1 2 3 4 5

(c)

Figure 7. Relationship between crowd density and perceived acoustic comfort level on the commercial pedestrian street with a traffic road (a); relationship between crowd density and perceived acoustic comfort level on the commercial pedestrian street without a traffic road (b) and on the underground shopping street (c)

Two videos and two audio recordings, which were recorded at the survey sites, were combined into four groups in post-production, where group A featured the video recorded at a low crowd density and the audio recorded at a low sound pressure level, group B featured the video recorded at a high crowd density and the audio recorded at a low sound pressure level, group C featured the video recorded at a low crowd density and the audio recorded at a high sound pressure level, and group D featured the video recorded at a high and the audio recorded at a high sound pressure level. Sixty-four volunteers were chosen to listen to the four groups of video and audio in the laboratory using headphones to simulate the conditions of the original environment. The volunteers were all graduate students of the same year; half of the them were men and half of them were women. These volunteers were trained to judge the sound level from the videos before the test to ensure they could accurately evaluate the acoustics. The volunteers were also divided into four groups, with 16 people per group, such that half of the total number of volunteers in each group were men and half were women. One group of volunteers was told to listen to one of the videos and to then evaluate the loudness of the video and their level of acoustic comfort.

Table 1 Influence of crowd density considering audiovisual effect.

	Group A	Group B	Mean difference between A and B	Group C	Group D	Mean difference between D and C
Subjective loudness	2.75	3.06	0.31**	3.51	3.75	0.24**
Acoustic comfort	3.02	2.81	-0.21**	3.25	2.93	-0.32**

** means significance $p<0.01$

The results are shown in Table 1 with the means and mean differences (t-test). Table 1 shows that the mean difference in subjective loudness between group B and group A was 0.31 with a significance of $p<0.01$, whereas the mean difference between group D and group C was 0.24 with a significance of $p<0.01$. This result shows that when the sound level is generally the same, users located in an area of high crowd density will evaluate subjective loudness as being high.

The mean difference in acoustic comfort level is also presented in Table 1, which shows that the mean difference between group B and group A was -0.21 with a significance level of

$p<0.01$, whereas the mean difference between group D and group C was -0.32 with a significance level of $p<0.01$. This result shows that when the sound level is generally the same, users in an area of high crowd density will evaluate their acoustic comfort level as being low.

4. Conclusions

Based on measurements and a questionnaire survey conducted in a traditional commercial pedestrian street and an underground shopping street, sound environments with different crowd densities were evaluated.

The influence of crowd density on sound levels was generally insignificant, when the crowd density was less than 0.05 persons/m^2, whereas the sound pressure level increased with crowd density when the crowd density was greater than 0.05 persons/m^2. This result was also indicated by theoretical calculations. The influence of crowd density on the sound pressure level was more significant in the underground shopping street than it was in the commercial pedestrian street, with an R^2 value of 0.437.

Traffic noise could not be completely masked when interviewees were located 10 to 20 m away from the traffic road, whereas when the interviewees were located 25 to 35 m away from the traffic road, the traffic noise was strongly masked, even when the crowd density was extremely low, i.e., 0.02, where less than 40% of the interviewees reported hearing traffic noise.

Regarding the other sound sources, the PA system was heard with greater frequency as the crowd density increased when the interviewees were located 10 to 20 m away from the traffic road, whereas the sound from the PA system gradually became masked as the crowd density increased when the interviewees were located 25 to 35 m away from the traffic road. The influence of crowd density on music from shops was insignificant: only 10-20% of the people could hear music from shops when the crowd density was either high or low. The sounds emanating from surrounding conversations could be enhanced as the crowd density increased regardless of whether the interviewees were near or far from the traffic road.

In evaluating acoustic levels, the influence of subjective loudness was also insignificant when the crowd density was less than 0.05 persons/m^2, whereas when the crowd density was greater than 0.05 persons/m^2, subjective loudness was enhanced the crowd density increased. It is interesting that the relationship between crowd density and acoustic comfort level was parabolic, i.e., when the crowd density was less than 0.10 persons/m^2 or greater than 0.25 persons/m^2, the acoustic comfort level was evaluated as being lower with decreasing or increasing crowd density. In the underground shopping street, the relationship between the crowd density and the acoustic comfort evaluation was also parabolic, where greater acoustic comfort was perceived at densities ranging from approximately 0.05 to 0.20 persons/m^2.

With respect to audiovisual influence, at essentially the same sound level, a higher crowd density was correlated with greater subjective loudness, and was correlated with lower acoustic comfort.

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