Effect of Soundscape Dimensions on Acoustic Comfort in Urban Open Public Spaces

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Abstract:
Soundscapes in public squares play important roles in urban open spaces. This study aimed to discover the effect of four soundscape dimensions, namely relaxation, communication, spatiality and dynamics, on acoustic comfort in urban open public spaces. A typical city square in China was selected as a case site. Sound environment measurements and questionnaire surveys were carried out for 8 survey positions. The results showed that the perceived dominance of sound sources had a significant effect on relaxation, communication, spatiality and dynamics. Relaxation was greater when the natural sound was perceived dominantly, while it was lower when mechanical sounds or anthropogenic sounds were perceived dominantly. Acoustic comfort had a significant correlation with the soundscape dimensions and LAeq, with spearman's correlation coefficients of 0.495 (relaxation), 0.210 (sound pressure level) and 0.288 (spatiality). In terms of the differences in perceived sound types, acoustic comfort was positively correlated with relaxation when natural sound or anthropogenic sound was perceived dominantly. As spatiality increased, acoustic comfort first decreased and later increased when relaxation was higher, while there were positive correlations between acoustic comfort and relaxation under the other situations. Moreover, when spatiality or communication was higher, there were significant correlations between acoustic comfort and dynamics. According to these results, acoustic comfort can be increased as soundscape dimensions change in an urban open public space.

Keywords: Soundscape dimension, urban open public space, acoustic comfort, sound environment, sound source

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1. *Introduction*

As urban open public spaces, squares usually play important roles in urban cultural activities, reflecting urban historical culture and art [1]. Previous studies have found that urban squares can be classified into five types: ceremonial, traffic, recreational, commercial and multifunctional [2]. With the development of urbanisation, squares will be increasingly multifunctional and integrated [3], and the crowd will be exposed to noise because of complex sound sources. Previous studies have generally focused on the influence and prevention of noise [4; 5]. For example, noise maps were developed in some European countries to predict the amount of traffic noise in squares [6; 7; 8; 9]. Different types of noise barriers have been developed in city squares to reduce traffic noise [10; 11]. However, these treatments, which only concentrate on noise control, often had limited impact on improving the quality of sound environments. Recently, particular attention has been paid to soundscapes, which involves the way people consciously perceive their environment and interdisciplinary efforts including physical, social, cultural, psychological and architectural aspects [12; 13]. Soundscapes, defined by ISO, are acoustic environment as perceived or experienced and/or understood by a person or people, in context [14]. In soundscape studies, different facets have been investigated, termed as soundscape dimensions, characteristics, factors, attributes etc., representing the general perception tendencies of soundscape, specific perception of soundscape, and objective measurement of soundscape [15, 16, 17, 18], although those terms are often used in a mixed way.

Acoustic comfort is the basic feeling of users towards the acoustic environment. Previous studies showed that acoustic comfort in urban open spaces can be affected by certain spatial and environmental factors as well as users' social and behaviours characteristics [18; 19; 20]. In terms of users' social and behaviours characteristics, Yang and Kang found that the duration and frequency of visits could affect the crowd's evaluation of acoustic comfort [21]. Similarly, in indoor spaces, Meng et al. found that dining styles and crowd density affected acoustic comfort [22, 23]. Some studies suggested that the social background and auditory experience in residents' daily lives might influence soundscape evaluation. Decreasing sound levels did not always improve acoustic comfort [21; 24]. Moreover, it has been found that the crowd's perception of sound might be influenced by physical factors such as temperature, humidity and sunlight [25; 26]. Torija et al. proposed a prediction model that analyses not only the equivalent continuous sound pressure level (LAeq) but also the temporal and spectral composition in the soundscape [27]. Raimbault et al. found that the perception of sound correlated with acoustic indicators such as background noise or the standard deviation of short LAeq [28]. Some landscape factors, such as water areas and greening measures, could adjust the perception of the sound environment [29]. Jeon et al. found that both tonality and fluctuation strength play major roles as sound quality metrics that describe subjects' acoustic comfort [30]. In terms of sound sources, anthropogenic sounds such as footsteps and voices were largely unaffected by visual perception [31]. Natural sounds such as that of water effectively enhance acoustic comfort in urban open public space [32]. Previous studies have revealed that the perception of traffic noise differs substantially from that of music [33].

Soundscape dimensions have been studied in urban open public spaces [34; 35; 36]. Raimbault et al. suggested three main categories of analysis: activity, such as human presence or transport; spatial attributes, such as location; and time history, such as moments or periods [28]. Keiji et al. found that three major dimensions, preference, activities and sense of daily life, affect soundscape evaluation [15]. Kang and Zhang, using a semantic differential method, found four main soundscape dimensions for urban open spaces: relaxation, communication, spatiality and dynamics [37]. Axelsson et al. made 100 subjects evaluate 50 different soundscapes and found three main dimensions of soundscape evaluation: pleasantness, eventfulness and familiarity [16]. Della Crociata et al. defined optimal intervals for selected parameters by comparisons with subjective "comfort" thresholds [38]. Aletta et al. [39] suggested that two major dimensions which are pleasantness and calmness affect soundscape, and a third potential dimension is the appropriateness of a soundscape to a place. They also found distinguishable or indistinguishable, background or foreground, and intrusive or smooth are three important dimensions in terms of sound sources [40]. Sudarsono et al. [17] revealed that three reliable soundscape dimensions are relaxation, dynamics and communication, which are consistent with the previous study conducted by Kang and Zhang [37]. Meng et al. also found that acoustic comfort correlated with subjective loudness [18]. It has also been indicated that there were correlations between perceptions of space, namely relaxation and acoustic comfort [41]. Davies et al. found that the sonic environment had two main components that might be associated with two emotions, namely "calmness" and "vibrancy," which are related to perceptions of the sound environments [35]. While the above studies are useful to understand soundscape from different dimensions, it is important to examine systematically the relationships between acoustic comfort and soundscape dimensions, which is also vital for implementing the soundscape approach in urban planning and design. Moreover, previous studies have mainly been developed in low-density cities, and it is needed to examine the situations in high-density cities [23].

This study therefore aims to reveal the relationship between acoustic comfort and soundscape dimensions. In this study, with a typical multifunctional square as an example, sound level measurements and questionnaire surveys were carried out. Four soundscape dimensions, namely relaxation, communication, spatiality, and dynamics, were selected for subjective measurement according to Kang and Zhang's research [37]. Among them, "Relaxation" represents soundscape dimension including quiet and pleasant [16, 17, 37]. "Communication" is the soundscape dimension relating to social, meaningful, smooth, etc. [17, 38]. "Spatiality" is mostly associated with echoed and far [17, 37]. "Dynamics" is principally related to varied and fast [37]. On the basis of the survey, the study first analysed the correlations between acoustic comfort and soundscape dimensions, and then examined the relationships between acoustic comfort and soundscape dimensions with different perceived sounds.

*2. **Methodology***

The methods included the selection of a survey site, a questionnaire-based survey, sound-level measurement, and statistics analysis.

2.1. Survey site

A city square, named Centennial Square, in Dalian, China, was selected as the case site, as shown in Figure 1. Dalian Centennial Square, a typical multifunctional square, is nearly a circle of 135 m wide. A 15m-wide road runs on the south side of the square, and the Bohai Sea is on the other side. There are some functional zones in the square for walking, eating, leisure, sightseeing, recreation and so on. These functional zones are common in China and most Asian countries [42]. Therefore, the results of this case study are likely to be applicable not only to other areas in China but also to similar cases in Asian countries.

A previous study found that the main sound sources in the case site are the sea, seagulls, amusement equipment, traffic noise and anthropogenic sounds [42]. Considering that the differences in the main sound sources might lead to diversity in the soundscape [25] and to ensure a suitable distance between survey positions, 8 survey positions were set near the edge of the square, 5 m away from the edge (where activity areas and main sound sources were located) to avoid instantaneous errors [43]. The survey scope was around 7.5 m for each survey position to ensure that the distance between the edges of each survey position is over 10 m [44]. Dalian Centennial Square is a famous tourist attraction for visitors and a source of leisure for local residents, so there are adequate samples of both sound sources and users for this study.

2.2 Questionnaire survey

In a study of soundscapes in urban open public spaces, Kang and Zhang found four soundscape dimensions, namely relaxation, communication, spatiality and dynamics [37]. These four dimensions were examined in our study. Acoustic comfort and subjective loudness are also important evaluation indicators for acoustic perception in urban open spaces [23]. Therefore, this study used the questionnaire survey to measure acoustic comfort, subjective loudness and soundscape dimensions in the survey locations [18; 45]. The questions were assessed using a five-point Likert scale [46], as shown in Table 1. To examine the effects of perceived sound types on acoustic comfort, respondents were asked to rank three kinds of perceived sounds (open question) [47]. Their answers were grouped according to the type of sound: natural, anthropogenic or mechanical [16; 48]. Then a statistical analysis of the perceived sounds proportion was performed in each survey position [49].

Before the formal investigation was conducted, the reliability and validity of the questionnaire were tested for suitability [50]. To ensure that the sampling was random, the survey was taken every 10 minutes orally by respondents. The research staff then completed each questionnaire within 3-5 minutes [51]. Considering that the differences in the basic physical environment might be caused by the time [29], the survey at the 8 positions was carried out from 9:00 am-11:00 am. During this time, the temperature and sunlight changed slightly [52] because the site was near the sea.

In terms of subjective investigation, 245 valid questionnaires were obtained at the survey sites, and each survey position questioned over 30 individuals [53]. Overall, 31 questionnaires were collected at position 1, 30 at position 2, 30 at position 3, 32 at position 4, 30 at position 5, 31 at position 6, 30 at position 7, and 31 at position 8. Split-half reliability was used to confirm the samples were sufficient for this study [53].

Fig. 1. Plan and survey positions of Centennial Square.

Table 1. The scale of the soundscape dimensions in the questionnaire.

	1	**2**	**3**	**4**	**5**
Acoustic comfort	Very uncomfortable	Uncomfortable	Adequate	Comfortable	Very comfortable
Subjective loudness	Very quiet	Quiet	Adequate	Noisy	Very noisy
Relaxation	Very unrelaxing	Unrelaxing	Adequate	Unrelaxing	Very relaxing
Communication	Very poor	Poor	Adequate	Good	Very good
Spatiality	Very enclosed	Enclosed	Adequate	Open	Very open
Dynamics	Very weak	Weak	Adequate	Strong	Very strong

2.3. Measurement of sound pressure levels

Previous studies indicated that the sound perception of urban open spaces could be affected by the sound pressure level [54]. After each questionnaire was completed, the equivalent continuous A-weighted sound pressure level (LAeq) was immediately recorded using an 801 sound level meter. During the measurement, the meter's microphone was positioned approximately 1 m away from any reflective surfaces and 1.2-1.5 m above the ground to reduce the effects of acoustic reflection [55]. The meters were set in slow and A-weighted mode, and a recording was taken every 10 seconds. A total of 1 minute of data was obtained in each survey position [25]. The mean value was calculated to obtain the corresponding LAeq.

2.4. Statistical analysis

SPSS 20.0 was used to establish a database of all the subjective and objective results. In this study, the data of acoustic comfort, subjective loudness and soundscape dimensions were ranked data. The non-parametric statistics were conducted for the analysis, say rank sum test, nonparametric test, spearman's correlation and the ordinal logistic regression test. Rank sum test was conducted to examine if the survey samples were sufficient and to test if there were significant differences in soundscape dimensions and acoustic comfort between high value group and low value group. Nonparametric test was used to test if there were significant differences in soundscape dimensions among 8 survey positions. Spearman's correlation for ranked data was conducted to test the correlations between acoustic comfort and soundscape dimensions, and the ordinal logistic regression test was used to find out the relationships between soundscape dimensions and acoustic comfort.

*3. **Results and analysis***

Based on the survey and measurement results, this section first presents relationships between acoustic comfort and soundscape dimensions, and then shows relationships between acoustic comfort and soundscape dimensions with different types of perceived sounds and different evaluation of soundscape dimensions.

3.1. Basic analysis of soundscape and sound environments

In terms of sound pressure level, the square's average LAeq was 67.3 dBA, $LAeq_{max}$ was 73.6 dBA and $LAeq_{min}$ was 61.8 dBA. Positions 4 and 7 which were located near the shops and playground entrance had the highest LAeq. The reason might be that many users fed doves in front of the shops. Positions 2 and 8 had the lowest LAeq as they were located at the transition zone of the square entrance to the seaside so that the crowd merely passed by and did not stay. The LAeq at positions 4 and 7 were about 7dBA higher than at positions 2 and 8. The results indicate that sound level might be increased with increasing crowd density, which is also confirmed in previous studies [23].

In terms of subjective loudness, communication had the widest range (σ=0.841), while the fluctuation of subjective loudness was minimum (σ=0.572). This might due to the characteristics of the square for leisure and its open space, so relaxation and spatiality were high. Because the sound sources around the site varied greatly, dynamics was low, and communication had a wide range of values.

In terms of the perceived sound types, Figure 2 indicates the frequency of sound sources which users perceived dominantly at each survey position. As Figure 2 shows, anthropogenic sound was dominantly perceived at positions 1 and 2. Both anthropogenic and mechanical sounds were dominantly perceived at positions 3, 7 and 8. Natural sound was dominant and anthropogenic sound was also perceived at positions 4 and 5. Anthropogenic sound was dominant and both natural sound and mechanical sound were also perceived at position 6. Therefore, there were four types of perceived sound in the case site, as shown in Table2: anthropogenic sound was dominant, both anthropogenic and mechanical sounds were dominant, natural sound was dominant and anthropogenic sound was auxiliary and anthropogenic sound was dominant and both natural and mechanical sounds were auxiliary. In this paper the categories of positions were named A, B, C and D, respectively, according to these types.

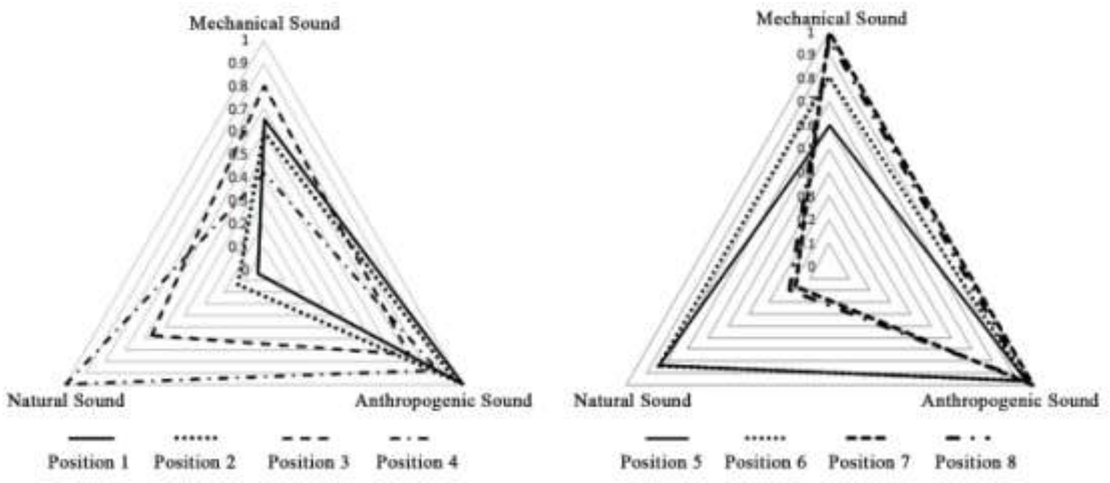

Fig. 2. The composition of perceived sounds at the survey positions.

Table 2. Categories of the survey positions according to the types of perceived sounds.

Categories	Survey positions	Type of sound source
A	Positions 1 and 2	Anthropogenic sound was dominant
B	Positions 3, 7 and 8	Both anthropogenic and mechanical sounds were dominant
C	Positions 4 and 5	Natural sound was dominant and anthropogenic sound was secondly perceived
D	Position 6	Anthropogenic sound was dominant and both natural and mechanical sounds were secondly perceived

Nonparametric test was conducted to examine if there were significant differences in soundscape dimension, as well as subjective loudness among the survey positions, and the results, as shown in Table 3, indicate that there were significant differences among four soundscape dimensions ($p<0.05$). However, there was no significant difference among subjective loudness ($p>0.05$). A possible reason is that subjective loudness is the subjective description of objective sound indicators and reflects the direct response to the sound pressure level of the listeners and it is only slightly influenced by the listeners themselves. The mean values of soundscape dimensions, acoustic comfort, subjective loudness, and LAeq were calculated and shown in Figure 3. It can be seen that relaxation, spatiality, and acoustic comfort all show a similar tendency.

In terms of relaxation, Table 3 shows that there were significant differences between position 4 and positions 2 and 7 ($p<0.05$), between position 5 and positions 1, 2 and 7 ($p<0.05$), and between position 6 and positions 1, 2 and 7 ($p<0.05$) respectively. While there were no differences in relaxation among the others. Positions 5 (M=4.10) and 6 (M=4.10) had the highest value of relaxation, while positions 2 and 7 had the lowest relaxation; their quantitative difference was within 0.5 dBA. According to Table 2, it can be seen that relaxation had a significant difference between the positions where anthropogenic sound was dominantly perceived, and the positions where natural sound was dominantly and anthropogenic sound was secondly perceived ($p<0.05$), as well as the positions where anthropogenic sound was dominant and both natural and mechanical sounds were secondly perceived ($p<0.05$). No difference was observed between the positions where anthropogenic sound was dominantly perceived and the positions where mechanical and anthropogenic sounds were dominantly perceived (p>0.05). The results show that relaxation was higher when natural sound could be perceived, while it was lower when anthropogenic or mechanical sound was dominantly perceived. A previous study in Japan [56] showed that natural sounds such as the twittering of birds and the murmuring of water topped the list of appealing sounds, while the least appealing sounds were mechanical, such as motorbikes, idling engines and construction. It can be seen that the crowd might feel relaxed when they are in their favorite sound environments. On the other hand, previous studies indicated that natural sounds can be masked by traffic noises [36] Therefore, when anthropogenic and mechanical sounds were dominantly perceived, the crowd felt least relaxed.

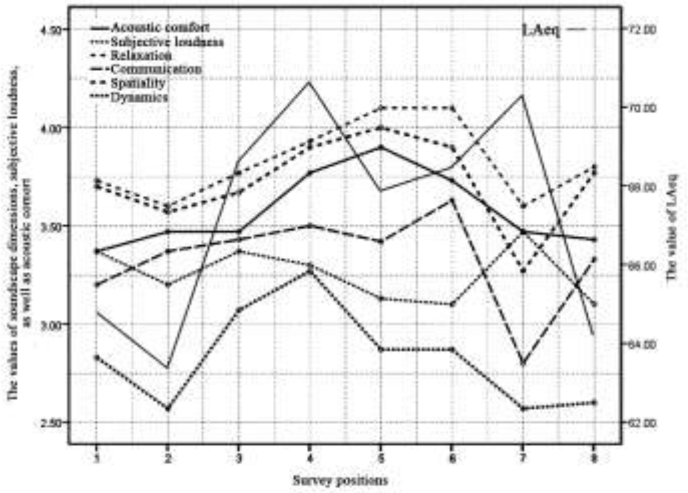

Fig. 3. The mean values of soundscape dimensions acoustic comfort, subjective loudness and LAeq.

Table 3. Difference in soundscape dimensions among the survey positions, where ★, with significant difference in relaxation; ○, with significant difference in communication; ◆, with significant difference in spatiality; □, with significant difference in dynamics.

Positions	1(A)	2(A)	3(B)	4(C)	5(C)	6(D)	7(B)	8(B)
1(A)	-			□**	★*	★*	○*◆*	○*
2(A)		-	□**	★*□**	★**◆*	★**	○**	
3(B)			-				○**◆*□**	
4(C)				-		□**	★*○**◆* *□**	
5(C)					-		★**○**◆**	
6(D)							★**○**◆**	
7(B)							-	○**◆**
8(B)								-

* p<0.05, ** p<0.01.

Communication might be influenced by the dominantly perceived sounds. As shown in Table 3, the communication is different between position 7 and the other positions (p<0.05) and between positions 8 and 1 (p<0.05), while there is no difference among the others. As shown in Figure 3, communication has generally no difference among positions 2 (M=3.37), 3 (M=3.43), 5 (M=3.43) and 8 (M=3.43). Position 6 (M=3.65) had the highest communication, while position 7 (M=2.80) had the lowest. A previous research found that communication is higher when anthropogenic sound was dominant [16]. Therefore, this result suggests that the anthropogenic sound occupied a certain proportion of the perceived sounds at each position. On the other hand, comparing position 7 with positions 3 and 8, which had the same perceived sounds composition, the $LAeq_{max}$ at position 7 was 70.3 dBA, which was 3-6 dBA higher than positions 3 and 8. These results indicate that communication could be changed by sound level.

Spatiality might also be influenced by the type of perceived sounds. As shown in Table 3, there were significant differences in spatiality between position 7 and positions 1, 3, 4, 5, 6 and 8 (p<0.05), and between positions 5 and 2 (p<0.05). Spatiality has no significant differences among the other positions. As shown in Figure 3, spatiality at position 7 was lowest (M=2.57) among the positions, which might have been caused by LAeq. The high LAeq might have influenced the crowd's evaluation of spatiality. Spatiality (M=4.00) was highest at position 5, possibly because it was near the sea, leading the crowd to have a strong sense of natural sound. Therefore, spatiality might increase with increasing natural sounds or sound level.

As shown in Table 3, there were differences in dynamics between position 4 and positions 1, 2, 6 and 7 (p<0.01), and between position 3 and positions 2 and 7 (p<0.01), while there was no among the others. As shown in Figure 3, position 4 was the highest (M=3.27). This might because the sounds from position 4 were mostly the cries of seagulls, which had strong rhythm. However, position 5 had the same perceived sound types as position 4 yet had a low value in dynamics. A possible reason for this outcome was that the crowd density was high around position 5 (M=2.72) and the proportion of anthropogenic sound was larger than that at position 4. Anthropogenic sounds were usually discontinuous and generated randomly with weak rhythms, which might have influenced the evaluation of dynamics. Therefore, natural sound might increase dynamics in the urban open public spaces, while anthropogenic sound might decrease dynamics.

According to the soundscape dimensions, the positions are classified into two groups (4 positions in each group). The group with higher value is named R1 (relaxation), C1 (communication), S1 (spatiality), and D1 (dynamics). The group with lower value is named R2 (relaxation), C2 (communication), S2 (spatiality), and D2 (dynamics). Rank sum test of soundscape dimensions and acoustic comfort was conducted between the high groups and the low groups. The result, as in Table 4, shows that there were significant differences between the two groups in relaxation, communication, spatiality and dynamics (p<0.05) and in the corresponding acoustic comfort (p<0.05) in terms of a given soundscape dimension. This means that differences in soundscape dimensions might cause differences in acoustic comfort. Figure 4 shows the value of acoustic comfort under different evaluations of soundscape dimensions. It can be seen that the acoustic comfort are reduced with decreasing relaxation, communication, spatiality and dynamics. Among these soundscape dimensions, relaxation affected acoustic comfort most, while spatiality affected acoustic comfort least.

3.2 Relationships between soundscape dimensions and acoustic comfort based on survey points

The 245 questionnaires were analysed using Spearman's correlation analysis to examine the correlations between acoustic comfort and soundscape dimensions as well as LAeq, and the results are shown in Table 5. Relaxation (R=0.495>0), spatiality (R=0.288>0) and LAeq (R=0.21>0) were positively correlated with acoustic comfort, and the significance of correlation coefficient was p<0.01 or p<0.05. Compared with spatiality and LAeq, relaxation (R=0.495>0.288>0.210) was significantly correlated with acoustic comfort.

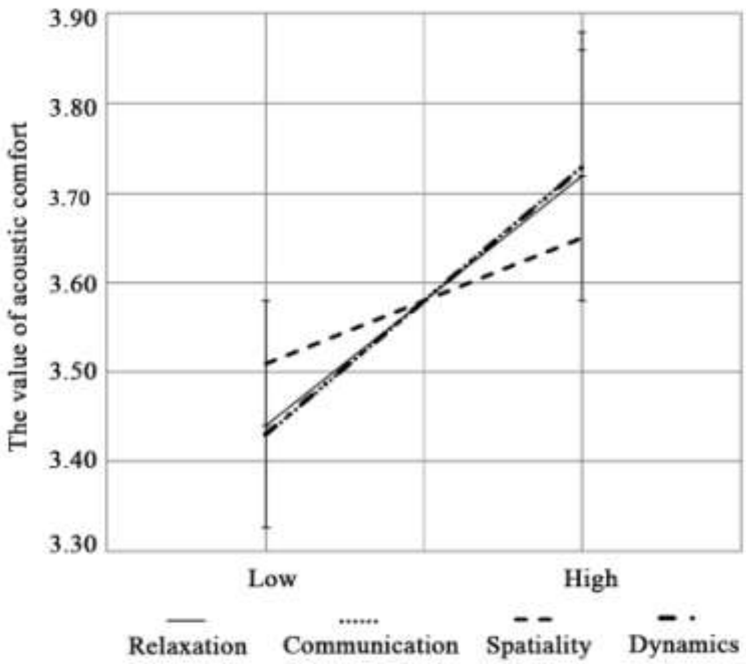

Fig. 4. Acoustic comfort with different values of the soundscape dimensions, where “Low” represents the group with lower value of corresponding soundscape dimensions; “High” represent the group with higher value of corresponding soundscape dimensions.

Table 4. Difference in soundscape dimensions and acoustic comfort between low and high value groups.

	Relaxation	**Communication**	**Spatiality**	**Dynamics**
Difference between low and high value groups	.000**	.000**	.049*	.000**
Difference in acoustic comfort between low and high value groups in terms of a given soundscape dimension	.001**	.000**	.017*	.000**

* *p*<0.05. ** *p*<0.01.

An ordinal logistic regression test between acoustic comfort and soundscape dimensions was performed. The test of parallel lines (p=0.348＞0.05) proved the results reliable. Relaxation had a significant influence on acoustic comfort. Comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.01, 0.04 and 0.25, respectively. The results (0.01<0.04<0.25) show that the acoustic comfort increases with increasing relaxation. It was similar to the findings of Viollon and Lavandier [57]. They found that relaxation played an important role with regard to the influence of affective impressions and preference in auditory judgement. Also, Cain et al. found that the two independent emotional dimensions of a soundscape were related to its “calmness” and “vibrancy” [58]. Section 3.1 shows that relaxation was higher when the natural sound was dominantly perceived, and the natural sound could mask other types of sounds in some cases. Therefore, increasing the richness and intensity of the natural sound in urban public open spaces can improve acoustic comfort.

Table 5. Correlations between soundscape dimensions and acoustic comfort.

	Relaxation	Communication	Spatiality	Dynamics	LAeq
Correlation coefficient	0.495	0.112	0.288	0.064	0.210
Significance	.000**	.082	.000**	.317	.010**

** p<0.01.

3.3. Relationships between soundscape dimensions and acoustic comfort based on perceived sounds

This section is to examine whether the correlations between soundscape dimensions and acoustic comfort can be affected by the different perceived sound types and the different evaluations of soundscape dimensions. Ordinal logistic regression test between acoustic comfort and soundscape dimensions was conducted under different conditions.

Groups A, B, C and D, as classified in Table 2, were analysed with ordinal logistic regression test with regard to different perceived sound types. As shown in Table 6, when natural sound was dominantly perceived, there was a significant correlation between relaxation and acoustic comfort, and acoustic comfort might increase as relaxation went up. Comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.007, 0.042 and 0.254, respectively. This result indicates that the acoustic comfort of perceived sound types increases with increasing relaxation. When natural sound was dominantly perceived and anthropogenic sound was secondly perceived, acoustic comfort might first rise and later fall with increasing relaxation. Ccomparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.181, 0.011 and 0.913, respectively. The acoustic comfort was lowest as relaxation was “adequate” (0.011<0.181<0.913). When both anthropogenic and mechanical sounds were dominantly perceived, anthropogenic sound was dominantly perceived and both natural and mechanical sounds were secondly perceived, there was no significant correlations between acoustic comfort and soundscape dimensions. The results demonstrate that when the crowd density in the square was high, the mainly perceived sound was anthropogenic.

The relationship between soundscape dimensions and acoustic comfort were also affected by different soundscape dimensions. As for relaxation, groups R1 and R2 were analysed with ordinal logistic regression test between soundscape dimensions and acoustic comfort, as shown in Table 7, where relaxation was significantly related to acoustic comfort. When the relaxation was high, comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.010, 0.024 and 0.369, respectively. Similarly, when relaxation was low, comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.004, 0.031 and 0.131, respectively. The acoustic comfort of perceived sound types increases with increasing relaxation (0.010<0.024<0.369, 0.004<0.031<0.131).

Comparing the results of ordinal logistic regression test between groups C1 and C2, it can be seen that the relationships between soundscape dimensions and acoustic comfort were affected by communication. As presented in Table 7, when communication was high, acoustic comfort was significantly associated with relaxation, as well as dynamics (p<0.05). Comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.009, 0.020 and 0.207, respectively. Comparing those who felt “weak” with “strong” with regard to dynamics, the probability of having the same level at “very comfortable” was reduced to 0.224. This result indicate that visitors felt more comfortable when they had a strong dynamics. On the other hand, when communication was low, relaxation was also significantly affected by acoustic comfort. Comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.005, 0.020 and 0.073, respectively. The acoustic comfort increases as relaxation increases (0.005<0.020<0.073). Previous studies have shown that anthropogenic sound leads to strong communication [16]; therefore, when the crowd density in the square is high, the intensity of natural sound should be increased to improve acoustic comfort. When the crowd density is low, natural sounds and soft music should be enhanced to improve acoustic comfort.

Table 6. Logistic regressive analysis between soundscape dimensions and acoustic comfort under different perceived sound types, where A: Anthropogenic sound was dominantly perceived. B: Both anthropogenic and mechanical sounds were dominantly perceived. C: Natural sound was dominantly perceived and anthropogenic sound was secondly perceived. D: Anthropogenic sound was dominantly perceived and both natural and mechanical sounds were secondly perceived. Dependent variable is acoustic comfort, and OR is odd ratios.

Categories of survey positions	**Relaxation**	**β**	**OR**
A	Very Unrelaxing	-	-
	Unrelaxing	-4.903^{**}	0.007
	Adequate	-3.182^{**}	0.042
	Relaxing	-1.371^{**}	0.254
	Very Relaxing	0	1
C	Very Unrelaxing	-	-
	Unrelaxing	-1.709^{*}	0.181
	Adequate	-4.534^{**}	0.011
	Relaxing	-0.091^{*}	0.913
	Very relaxing	0	1
B	-	-	-
D	-	-	

* p<0.05. ** p<0.01.

With regard to spatiality, comparing the results of ordinal logistic regression test between groups S1 and S2, the difference of spatiality influenced the correlation between soundscape dimensions and acoustic comfort. As shown in Table 7, when the spatiality was high, there was correlation between relaxation and acoustic comfort (p<0.05). Comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.015, 0.008 and 0.207, respectively. This shows that the probability of feeling comfortable increases with increasing relaxation (0.008<0.015<0.207), suggesting that increasing relaxation might not always improve acoustic comfort; acoustic comfort might be the lowest when relaxation was moderate. A possible reason for this outcome was that when the spatiality was high, the space was usually open, so the wide view might affect the evaluation of acoustic comfort. Similarly, the dynamics was also correlated with acoustic comfort (p<0.05). Comparing those who felt “weak” and “strong,” with regard to dynamics, the probability of having the same level at “very comfortable” was 0.224. This result indicated that visitors were more likely to feel comfortable when the sounds had a strong dynamics. However, when spatiality was low, only relaxation was related to acoustic comfort (p<0.05). Comparing those who felt “unrelaxing,” "adequate" and "relaxing," with "very relaxing," the probability of having the same level at "very comfortable" was 0.007, 0.119 and 0.394, respectively. The likelihood of feeling comfortable increased with increasing relaxation (0.007<0.119<0.394), which meant that acoustic comfort might increase as relaxation rise. Therefore, when spatiality is high, adjusting the landscape and the intensity of natural sound would increase acoustic comfort. When spatiality is low, strategies should be implemented, such as increasing the natural sound.

Table 7. Logistic regressive analysis between soundscape dimensions and acoustic comfort under different evaluations of dimensions, where R1: Relaxation high. R2: Relaxation low. C1: Communication high. C2: Communication low. S1: Spatiality high. S2: Spatiality low. D1: Dynamics high. D2: Dynamics low. Dependent variable is acoustic comfort, and OR is odd ratios.

Categories of survey positions	**Relaxation**	**Dynamics**	**β**	**OR**
R1	Very unrelaxing		-	-
	Unrelaxing		-4.619**	0.010
	Adequate		-3.715**	0.024
	Relaxing		-0.998*	0.369
	Very relaxing		0	1
R2	Very unrelaxing		-	-
	Unrelaxing		-5.552**	0.004
	Adequate		-3.489*	0.031
	Relaxing		-2.030*	0.131
	Very relaxing		0	1
C1	Very unrelaxing		-	-
	Unrelaxing		-4.749*	0.009
	Adequate		-4.010**	0.018
	Relaxing		-0.676*	0.509
	Very relaxing		0	1
		Very weak	-	-
		Weak	-1.498*	0.224
		Adequate	-	-
		Strong	-	-
		Very strong	0	1
C2	Very unrelaxing	-	-	-
	Unrelaxing		-5.396**	0.005

	Adequate		-3.900**	0.020
	Relaxing		-2.623*	0.073
	Very relaxing		0	1
S1	Very unrelaxing		-	-
	Unrelaxing		-4.209**	0.015
	Adequate		-4.811**	0.008
	Relaxing		-1.573*	0.207
	Very relaxing		0	1
		Very weak	-	-
		Weak	-1.422*	0.241
		Adequate	-	-
		Strong	-	-
		Very strong	0	1
S2	Very unrelaxing		-	-
	Unrelaxing		-4.976**	0.007
	Adequate		-2.132*	0.119
	Relaxing		-0.932*	0.394
	Very relaxing		0	1
D1	Very unrelaxing		-	-
	Unrelaxing		-4.749*	0.009
	Adequate		-4.010**	0.018
	Relaxing		-0.676*	0.508
	Very relaxing		0	1
D2	Very unrelaxing		-	-
	Unrelaxing		-5.396**	0.005
	Adequate		-3.900**	0.020
	Relaxing		-2.623*	0.073
	Very relaxing		0	1

* p<0.05. ** p<0.01.

From the analysis with ordinal logistic regression test between acoustic comfort and soundscape dimensions of groups D1 and D2, dynamics could affect acoustic comfort's correlation with soundscape dimensions. As shown in Table 7, no matter what the dynamics were, relaxation significantly correlated with acoustic comfort (p<0.05). When the dynamics was high, comparing those who felt "unrelaxing," "adequate" and "relaxing," with "very relaxing," the probability of having the same level at "very comfortable" was 0.009, 0.020

and 0.207, respectively. On the other hand, when the dynamics was low, comparing those who felt “unrelaxing,” “adequate” and “relaxing,” with “very relaxing,” the probability of having the same level at “very comfortable” was 0.005, 0.020 and 0.073, respectively. The results show that the probability of feeling comfortable increases with increasing relaxation (0.009<0.020<0.207, 0.005<0.020<0.073) no matter what the dynamics is, which means that acoustic comfort might increase as relaxation is increased.

4. Conclusions

This study showed the influence of soundscape dimensions on acoustic comfort according to a questionnaire survey and acoustic measurements at a typical square in China.

Regarding to the sound sources that user perceived, different types of them played remarkable roles in acoustic comfort, relaxation, communication, spatiality and dynamics. Relaxation was higher when natural sound was dominantly perceived, while when mechanical sound was dominantly perceived, relaxation was the lowest, and their quantitative difference was within 0.5. Communication was higher when anthropogenic sound was dominantly perceived, which differed when mechanical sound or sound level increased. A difference in spatiality was caused by changes in sound pressure level, and spatiality decreased as LAeq increased. Perceived anthropogenic and mechanical sounds might cause poor dynamics because they were discontinuous and random, while natural sounds had strong rhythm and might lead to high dynamics. However, subjective loudness was not affected by the perceived sounds.

Regarding the correlation between acoustic comfort and soundscape dimensions, relaxation, spatiality and sound pressure level had significant correlation with acoustic comfort. Relaxation had moderately positive correlation (R=0.495, p<0.01) with acoustic comfort, and LAeq (R=0.210, p<0.05) and spatiality (R=0.288, p<0.01) had weak positive correlation with acoustic comfort.

When the perceived sound types and the evaluations of soundscape dimensions were different, the relationship between acoustic comfort and dimensions was further analysed. With regard to different perceived sound types, the correlation between relaxation and acoustic comfort was significantly positive when anthropogenic or natural sounds were dominantly perceived. When there was no dominantly perceived sound, there was no difference in correlations between acoustic comfort and soundscape dimensions. Relaxation significantly correlated with acoustic comfort whatever the value of the dimensions, and the correlation was positive in most cases. When spatiality was strong, acoustic comfort first rose and then fell with increasing relaxation. When communication or spatiality was strong, dynamics had significant positive correlation with acoustic comfort.

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