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Development of indicators for the soundscape in urban shopping streets

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Abstract

This paper aims to find a series of objective indicators that can fully describe the soundscapes of urban shopping streets. The perceptual and physical features of soundscapes in urban shopping streets have been investigated via field surveys and a laboratory study. Using the semantic differential method, the perception structure of shopping street soundscapes was initially analysed, and five major perceptual factors were identified that explained 64% of the total sample variance, including preference, loudness, communication, playfulness and richness. Each perceptual factor explained approximately 10% to 15% of the total variance, which showed that they shared very similar importance in the representation of the overall soundscapes in urban shopping streets. Based on this semantic differential analysis, a laboratory study was performed to investigate the relationship between perceptual factors and physical indicators. Sound levels and psychoacoustic indicators were initially considered to be the most common indicators. The results showed that there were significant correlations between these indicators and three perceptual factors, including preference, loudness and communication. A new indicator (dynamic spectrum centre or DSC) was then developed in this study based on the concepts of spectrum gravity centre analysis and temporal variety analysis. This indicator combined spectral and temporal analysis to describe the contents of background sounds and sound events. The DSC indicator was found to have a significant correlation with the other two perceptual factors (playfulness and richness). Increasing the variability of the sound event (a higher standard deviation of DSC_E) could make soundscape more playful and richer.

1 Introduction

Many studies focusing on soundscapes in urban spaces have been conducted in the last few decades. These studies show that the perception of a soundscape depends strongly on the location and the sound sources [1, 2, 3, 4, 5]. Therefore, many studies turned to focus on specific acoustic environments, such as natural areas and city squares. In China and many other countries, shopping streets have become one of the most basic and important components of urban areas in the past several decades and account for multiple functions, including tourism, dining, relaxation, shopping, etc. The presence of multiple functions causes high sound levels and complex sound sources. These features result in a very different soundscape from other spaces, such as urban parks. However, very few studies have focused on soundscapes in urban streets [6, 7, 8].

One key task in the study of urban soundscape is developing objective indicators for further policy making and acoustical environment monitoring. With the current laws, regulations and standards for open urban acoustical environments, sound level indicators, such as A-weighted equivalent sound level (L_{Aeq}) and Day-night equivalent sound level (L_{day}, L_{night} and L_{den}), are considered as the standardized assessment indicators [9, 10]. However, many studies show that the perception of a sound environment is very complex and depends on more than simply the sound level [11, 12].Various indicators were developed by quantifying different aspects of sound signals to describe different features of a soundscape, such as the frequency spectrum, temporal composition, amplitude and spatial difference [13, 14, 15]. In this field, the outstanding works in psychoacoustics should be noted. Psychoacoustic analysis has been well developed and serves to quantify the subjective response of sounds by physical indicators, including loudness, sharpness, roughness, fluctuation strength, etc. [16]. In recent studies of the urban soundscape, psychoacoustic indicators, together with other indicators, were widely used in the soundscape category and sound source identity [17, 18, 19, 20].

Though many indicators have been suggested by previous studies, the question remains as how to fully describe urban soundscapes with objective indicators. One important reason is that the urban soundscapes are so complex that, in addition to acoustical properties, many other factors have strong influences on acoustic environment evaluation, including physical, psychological, social and cultural factors [5, 21, 22, 23, 24]. A single indicator can only describe certain aspect of urban soundscapes. Therefore, it is important to identify major factors of soundscape perception, which could identify a basic framework for further studies. A psychological method was introduced into urban soundscape studies to describe how people perceive the sound environment, which is the semantic differential method [25]. In the past decade, the semantic differential method has been proved to be a useful method in identifying the perception structure of a sound environment [26, 27, 28].

The aim of this study is to find a series of objective indicators that can fully describe soundscapes in urban shopping streets. First, the main perceptual factors of the soundscape were identified through a field survey using the semantic differential method, which established a framework for further analysis. The relationship between the physical indicators and major perceptual factors was then analysed through a laboratory study. In this part, some common indicators were firstly considered, including sound level and psychoacoustic indicators. In addition, a new method was also developed by analysing both temporal and spectral features of the acoustic environment.

2 Method

2.1 Field survey

In the past decade, the semantic differential method has been proved to be a useful tool for describing the emotional structure of acoustic environment perception. Raimbault identified two cognitive modes for representing urban soundscapes of main thoroughfares, pedestrian districts, playgrounds and market squares: (i) "descriptive listening" mode and (ii) "holistic hearing" mode, which highlight the heterogeneous judgements of people. [29] Combined with hierarchical cluster analysis, the difference between city park soundscape and suburban green area soundscape were revealed. [30] Through a factor analysis process, the semantic scales could be divided into several groups which indicated the major perceptual factors of soundscape perception. Earlier studies focused on individual sounds [26, 27] and then expanded to environmental sounds. Four essential factors were found in residential areas: adverse, reposing, affective and expressionless [28]. For general urban environment sounds, four main factors were suggested: evaluation, timber, power and temporal change [31]. For urban open public spaces, Kang and Zhang identified four factors from a cross-cultural study: relaxation, communication, spatiality and dynamics [32]. Focusing on traffic noise and construction noise, two main factors were identified by Jeon et al. [33] In some recent relevant studies, pleasantness and arousal were suggested based on laboratory studies [17, 18].

2.1.1 Survey sites selection

By comparing the results of previous studies, it is indicated that the results of the semantic differential method might be affected by the study method. By laboratory experiments, two or three main factors were extracted [17, 18, 27], whereas more factors were identified in studies that use field surveys [28, 32]. These results revealed that there were unavoidable differences between recordings and real urban soundscapes. To represent the real subjective responses from the users of urban shopping streets, the semantic differential analysis was performed using field surveys in this study, and six different streets were sampled.

As suggested by a previous study, scale factor is a dominating factor for urban street spaces [34]. The sample streets in this study were selected according to the scale factor to represent most common urban shopping streets. To ensure a greater sense of comfort and security in a street canyon, the width of urban shopping streets should be in the range of 8 m to 25 m [34]; Jacob also listed some famous European urban streets that fall within this range [35]. Considering researches of sound environment in street space, similar width range was also considered as the common width of urban streets [36]. In this study, the width range of 5 m to 30 was considered as the common width for urban shopping streets. To cover the width range of 5 m to 30, six different streets were sampled in two cities: Beijing (street 1, 2, 3) and Tianjin (street 4, 5, 6). Table 1 shows the basic information about the survey streets. The widths of the sampled streets vary from 5 m to 30 m. The lengths of the sampled streets vary from 150 m to more than 1 km. Meanwhile, in terms of function, some main functions were included in the sampled streets, including shopping, tourism, relaxing, dining, etc. All six shopping streets are multiple functional streets with more than three functions for each street. The sound sources that appeared in the survey sites were also investigated. The most common sound sources in the sampled shopping streets were sounds generated by human activity, whereas natural sounds were rarely heard.

Table 1. Basic information about the survey sites, where ○ means this function/sound appeared in the survey site.

			Shopping streets					
			1	2	3	4	5	6
Function	1	Shopping	○	○		○	○	
	2	Tourism	○	○	○	○	○	○
	3	Relaxation		○	○			○
	4	Dining	○		○	○		○
Spatial Scale	1	Width /m	25~30	15~25	5~10	20~25	15~25	5~10
	2	Height /m	40-50	25-50	<10	40-50	<10	<10
	3	Length /m	810	350	200	1100	1200	150
Sound Source	1	Man-made	○	○	○	○	○	○
	2	Natural			○			○
	3	Vehicle	○	○	○	○	○	
	4	Music	○		○	○	○	○
	5	Broadcasting	○			○	○	

Figure 1 shows the sound levels of the six survey sites. During the surveys, measurements of the sound levels (including 5 min of A-weighted equivalent sound level/L_{Aeq} and the cumulative statistical sound level of L_{10} and L_{90}) were also taken at each survey site. The results show that the sound level (L_{Aeq}) ranges from approximately 55 to 80 dBA. Meanwhile, the differences between L_{10} and L_{90} are quite similar for the six survey sites, which indicates that the sound levels were caused by sound events and background sounds. The range of sound level in this measurement (approximately 55 to 80 dBA) is used to decide the sound level range for the laboratory studies.

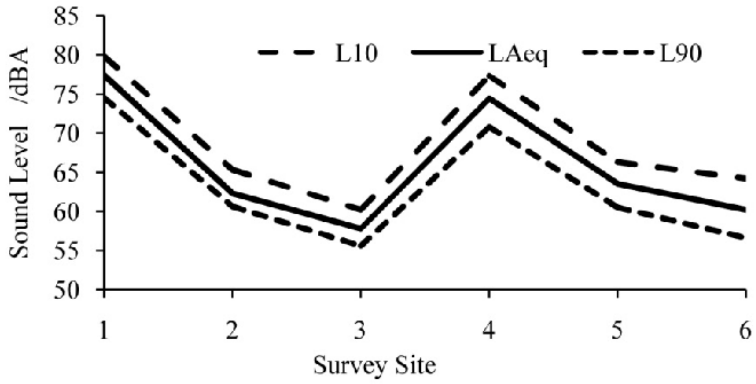

Figure 1. Sound levels of the sampled shopping streets measured in the survey.

2.1.2 Semantic differential questionnaire

One key issue in the semantic differential method is the selection of a set of semantic descriptors to form the questionnaire. A series of semantic differential descriptors were suggested by previous research on urban soundscapes [17, 18, 32]. To ascertain the unique characteristics of urban shopping streets, a pre-survey interview on soundscape assessment was performed to extract more descriptors. Total twenty-four semantic indicators were summarized from previous studies and pre-survey interview, which covered various aspects of a soundscape, including: relaxing-intense, friendly-unfriendly, comfortable-uncomfortable, beautiful-ugly, like-dislike, harmonious-disharmonious, crowded-capacious, lively-depressed, strong-weak, light-heavy, quiet-noisy, calming-agitating, sharp-flat, pure-impure, simple-varied, ordered-disordered, changing-steady, directional-everywhere, bright-dark clear-muffled, far-close, interesting-boring, meaningful-meaningless, and natural-artificial. A seven-point bipolar rating scale was used for the questionnaire. It should be noted that some of the descriptors were found to be confusing or difficult to evaluate, so only 18 descriptors remained in the later semantic differential analysis, which are shown in Table 2.

Table 2. Semantic indicators used in the semantic differential survey

Indicators	Extremely	Very	Little	Neutral	Little	Very	Extremely	Indicators
beautiful	-3	-2	-1	0	1	2	3	ugly
relaxing	-3	-2	-1	0	1	2	3	intense
friendly	-3	-2	-1	0	1	2	3	unfriendly
like	-3	-2	-1	0	1	2	3	dislike
harmonious	-3	-2	-1	0	1	2	3	disharmonious
clear	-3	-2	-1	0	1	2	3	muffled
directional	-3	-2	-1	0	1	2	3	everywhere
ordered	-3	-2	-1	0	1	2	3	disordered
weak	-3	-2	-1	0	1	2	3	strong
light	-3	-2	-1	0	1	2	3	heavy
quiet	-3	-2	-1	0	1	2	3	noisy
comfortable	-3	-2	-1	0	1	2	3	uncomfortable
lively	-3	-2	-1	0	1	2	3	depressed
interesting	-3	-2	-1	0	1	2	3	boring
meaningful	-3	-2	-1	0	1	2	3	meaningless
pure	-3	-2	-1	0	1	2	3	impure
simple	-3	-2	-1	0	1	2	3	varied
changing	-3	-2	-1	0	1	2	3	steady

2.1.3 Subjects

Table 3 shows basic information about the semantic differential survey subjects for the six different streets. Out of a total of 500 questionnaires, 493 valid questionnaires were collected. All interviewees were selected randomly, including local users (77%, 371/493) and tourists (23%, 122/493). As suggested by previous studies, the number of samples for the semantic differential method should be larger than 150 [32]. In order to find the appropriate sample number for this study, factor analysis was applied when the sample number reached 200, 300, 400 and 500 in this study. The result showed that the main factors extracted became very stable after the sample number reached 300, which indicated that the sample number in this study was enough.

The average age of the subjects is 26.5, and 80.1% of them are between the ages of 20 and 40. In terms of gender, 55.2% of the subjects were women and 44.8% were men. A balanced gender distribution was found in all of the street surveys, and the age distribution of the subjects in most of the survey sites was also very similar.

Table 3. Basic information about the subjects of the semantic differential survey

		Shopping streets						
		1	2	3	4	5	6	Total
Number of subjects		87	44	66	112	97	87	493
Gender distribution	Male	44(50.6%)	20(45.5%)	34(51.5%)	45(40.2%)	43(44.3%)	35(40.2%)	221(44.8%)
	Female	42(49.4%)	21(54.5%)	31(48.5%)	66(59.8%)	53(55.7%)	48(59.8%)	272(55.2%)
Age(20 to 40)		44(50.6%)	33(75%)	60(90.9%)	102(91.9%)	80(82.5)	76(87.4%)	395(80.1%)

2.2 Laboratory study

To conduct an acoustic analysis and avoid the influences of other factors, such as light and heat, a laboratory study was performed to investigate the relationship between perceptual factors and objective indicators. In a semi-anechoic chamber, the subjects were asked to evaluate the perceptual factors of a series of sound recordings. All sound recordings used in the experiment were acoustically analysed. Finally, a correlation analysis was applied to identify the relationship between perceptual factors and physical indicators.

Table 4. Emotional dimensions and corresponding semantic indices used for soundscape evaluation in a laboratory experiment.

Perceptual Factors	Indices	Extremely	Very	Little	Neutral	Little	Very	Extremely	Indices
Preference	beautiful relaxing friendly like harmonious	-3	-2	-1	0	1	2	3	ugly intense unfriendly dislike disharmonious
Communication	clear directional ordered	-3	-2	-1	0	1	2	3	muffled everywhere disorder
Loudness	weak light quiet comfortable lively	-3	-2	-1	0	1	2	3	strong heavy noisy uncomfortable depressed
Playfulness	interesting meaningful	-3	-2	-1	0	1	2	3	boring meaningless
Richness	impure varied changing	-3	-2	-1	0	1	2	3	pure simple steady

2.2.1 Experiment process

The experiment was performed in a semi-anechoic chamber, in which the background noise level was approximately 20 dBA. The semantic differential analysis was performed before the laboratory study, and some main perceptual factors were identified. During the experiment, the subjects were asked to evaluate the main perceptual factors of the recordings. Table 4 shows the main perceptual factors and corresponding semantic indices used in the laboratory experiment. To help the subjects evaluate the main factors, all perceptual factors were explained using semantic differential descriptors. A seven-point numerical scale was used, and a higher evaluation value meant that the soundscape presented to the subjects was more disliked, noisier, less playful, more monotonous and communication was more difficult. After the experiment, a correlation analysis was applied to investigate the relationship between perceptual factors and acoustical indicators.

In order to avoid the differences between the original signals from the computer and the signals that the subjects received, the acoustic stimuli were presented through a loudspeaker (Nor280 and Nor276, Norsonic) in this study, and the sound signals used for the acoustic analysis were recorded again at the location of the subject’s ear following the laboratory experiment. All sound stimuli were played randomly to each subject to avoid the influence of sound stimuli order.

2.2.2 Sound clips used in the experiment

All sound samples used in this study were from field recordings. Before the laboratory study, over 1000 min of audio recordings were collected (Norsonic Nor140, 48 kHz sampling rate, single channel) on the six shopping streets in the semantic differential survey. Afterward, 48 sound clips were made from this audio content and used in the experiments. In relevant studies, the durations of the sound clips are mostly in the range of 10 to 30 seconds. To ensure that the audio clips were long enough to fully represent the information in a real soundscape, the duration of each clip in this study was 1 min.

As shown in Table 1 there are all kinds of sound sources, in real shopping streets. In order to represent the real complex soundscape, each sound contained more than one sound source, and all the sound sources appeared during our survey and in the field recordings were contained in the experiment materials, including traffic sound, human talking, footsteps, music, construction sound and so on. The context of each sound clip is shown in Figure 2 using the sound source category suggested by A.L. Brown. [2]

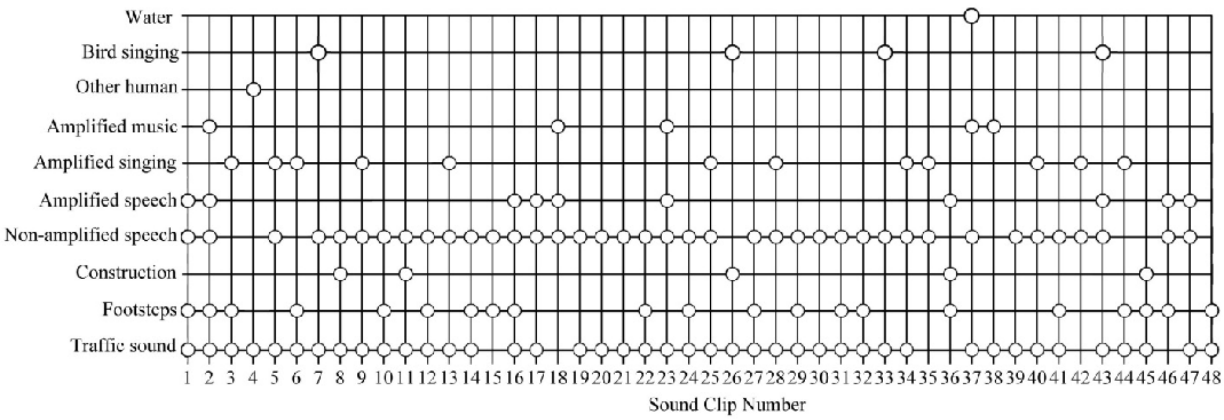

Figure 2. Sound source category of sound clips used in the laboratory experiment. where ○ means this sound source appeared in the sound clips.

2.2.3 Subjects

Totally 30 subjects participated in the laboratory experiment. All 30 subjects were university students (20 to 30 years old,), who were very similar with the major property of the subjects of the field survey and the main user of urban shopping street. All the participants were reported as normal hearing.

2.2.4Physical indicators

An acoustical analysis was conducted on all sound clips to calculate the physical indicators. Some recent studies on urban soundscapes have used psychoacoustic indicators and sound level indicators, which proved to be effective for describing subjective responses to urban soundscapes. Rychtáriková devised soundscape categories based on sound level and psychoacoustic indicators [20]. Yang proved that this set of indicators could be used to identify the sound contents [19]. In this study, a similar set of physical indicators was firstly considered, including equivalent sound level (L_{Aeq} and L_{eq}), cumulative statistical sound level (L_{10}, L_{50} and L_{90}), loudness, sharpness, roughness and fluctuation strength.

It should be noted that there is more than one calculation method for some psychoacoustic indicators, and the method suggested by Zwicker and Aures was used in this study [37, 38]. All indicators were calculated using Artemis software. The psychoacoustic indicators were well developed to quantify the subjective response to sounds by physical indicators [16]. Loudness is defined as the intensity sensation and considers the characteristics of the human hearing system and masking effects. Sharpness is developed based on loudness and describes the timbre sensation of the sound signal, which can be considered the gravity centre of the weighted specific loudness curve. Roughness and fluctuation strength are used to describe the sensation caused by amplitude-modulated sounds. If the modulation frequency is very low, the sensation produced is a fluctuating sound. As the modulation frequency increases, the sensation of roughness starts to increase.

There are some other indicators that were also used to evaluate the urban soundscapes [39, 40]. However, these indicators may be significantly influenced by the calculation and filtering methods, and there is no standard software for calculating them. Therefore, these indicators were not considered in this study.

2.3 Development of a combined spectral-temporal analysis: dynamic spectral centre analysis (DSC)

The correlation analysis presented in Section 3.3 (vide infra) found that the sound level indicators and psychoacoustic indicators were not able to describe the cultural aspects of soundscapes. Therefore, a new indicator was developed in this study.

As suggested by previous studies, the sound source is one of the key elements of soundscape perception. [11, 41, 42] Many indicators have been proposed to explain the effects caused by sound sources based on the concept of spectral analysis or temporal analysis [16, 39, 40]. However, these indicators have disadvantages when applied to urban soundscapes. Spectral indices, such as spectral gravity centre and sharpness, ignore the fact that the sound sources are constantly changing. And temporal analysis, such as TSLV (temporal sound level variability), cannot describe the content of the sound. To describe the cultural features of the urban soundscape, a new analysis method (dynamic spectral centre analysis, or DSC) was developed in this study. This method focused on the soundscape composition, which has been suggested to be an essential factor in soundscape perception [43, 44]. In contrast to other indicators, dynamic spectral centre analysis (DSC) combines spectral analysis and temporal analysis to reveal the composition of sound events and background sounds separately.

This technique is inspired by the concept of the gravity centre of spectrum [12, 39].The basic idea of the DSC analysis is to separate the sound events from background sounds with a temporal sound level analysis and then use the gravity centre of spectrum to reveal the composition of each part separately. Similar to the definition suggested by Bérengier, in this study, the gravity centre of spectrum (SC) of a certain sound clip is defined as

$$\mathrm{SC} = \frac{\int_0^{dt} f \cdot P(f)^2 \cdot df}{\int_0^{dt} P(f)^2 \cdot df}$$

where f is the frequency and P(f) is the corresponding sound pressure. Figure 3(A) is the schematic diagram of the SC indicator. The physical meaning of SC can be considered to be the gravity centre of the energy spectrum, which indicates where the major spectral component lies.

To apply the temporal analysis, the entire sound clip was divided into small, equal calculation units with a duration of dt; in this study, dt=100 ms. The calculation of SC is applied to each calculation unit to obtain the realtime SC indicator, which can be considered a function of time t, and this is referred to as the DSC.

Another important process of this method is to describe the spectral distribution of a sound event and background sounds separately. Therefore, one key issue in this method is how to automatically identify a sound event from the background sounds. A reasonable assumption is that if there is a sound event, the sound level would be higher than that of only background sounds. Therefore, in this study, this problem is resolved by applying a dynamic process to compare the realtime equivalent sound pressure level, Leq_t, and the overall equivalent sound pressure level for the whole clip, Leq_T. In the program, the equivalent sound pressure level for each unit was calculated and considered to be the realtime equivalent sound pressure level, Leq_t. If the realtime equivalent sound pressure level is higher than the overall equivalent sound pressure level (Leq_t>Leq_T), the sound event is considered to exist within this time unit, as the schematic diagram shows in Figure 3(C).

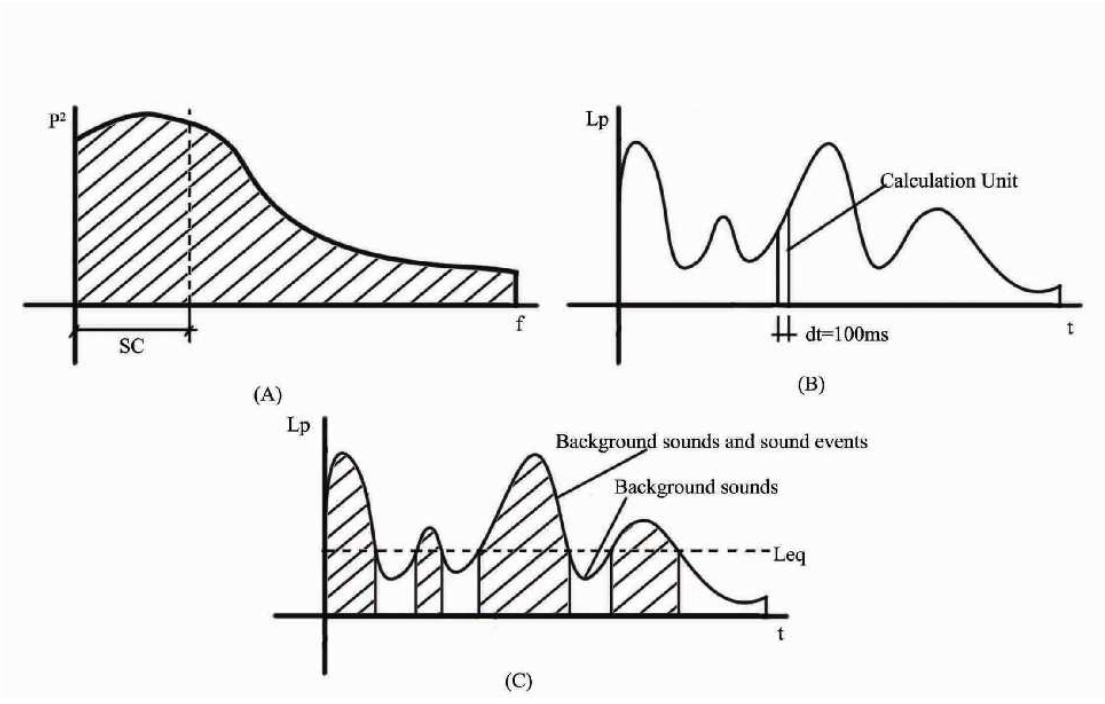

Figure 3. The definition of spectral centre (A), the schematic of a calculation unit (B) and the sound source category process (C).

In the process above, the sound clips are divided into two parts—one part with only background sound and one with background sounds and sound events.

(1) DSC of the background sound

Once the calculation unit with only background sounds was identified, it is easy to calculate the average value and standard deviation of the DSC of these units using simple statistical methods, which were called DSC_B_AVE and DSC_B_STD, respectively.

(2) DSC of a sound event

The calculation of the DSC of a sound event is more complex because in these units, both the background sound and sound event are present. For a certain unit, the sound level of the sound event can be calculated as

$$\mathrm{Leq\_E} = 10\lg(10^{\frac{\mathrm{Leq}}{10}} - 10^{\frac{\mathrm{Leq\_B}}{10}})$$

where Leq, Leq_B and Leq_E are the equivalent sound pressure levels of the entire unit, the background sound within the unit and the sound event within the unit, respectively.

According to the definition of SC as the gravity centre of the energy spectrum, there are certain relationships among the sound event, background sound and overall calculation unit, as shown in Figure 4.

$$S_B \cdot SC_B + S_E \cdot SC_E = S \cdot SC$$

where S_B and S_E are the area generated by background sound and the sound event in the energy spectrum.

$$S = \int P^2(f)df$$

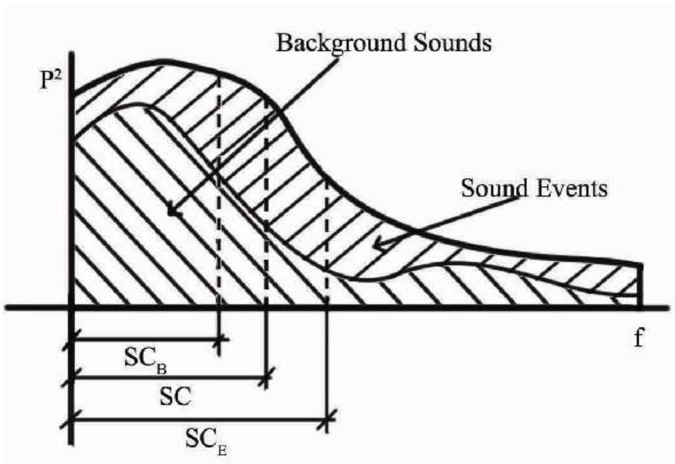

Figure 4. Relationship between the SC indicator of a sound event and that of background sounds in a calculation unit.

It can be concluded that

$$E_E \cdot SC_E + E_B \cdot SC_B = E \cdot SC$$

where E_E is the sound energy of sound events, E_B is the sound energy of background sounds, and E is the sound energy of all sounds within the unit.

$$\mathrm{Leq} = 10\lg\left(\frac{E}{E_{ref}}\right)$$

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Therefore, the SC of a sound event can be calculated as

$$\mathrm{SC_E} = \frac{\mathrm{SC} * 10^{\frac{\mathrm{Leq}}{10}} - \mathrm{SC_B} * 10^{\frac{\mathrm{Leq\_B}}{10}}}{10^{\frac{\mathrm{Leq}}{10}} - 10^{\frac{\mathrm{Leq\_B}}{10}}}$$

An assumption was made to simplify the calculation process in which, in these units, the sound level of the background sounds is equal to the overall equivalent sound pressure level of the clip, Leq_T, whereas the SC of the background sound in this unit is equal to the average value of the DSC of background sounds, DSC_B_AVE.

$$\mathrm{Leq\_B} = \mathrm{Leq\_T}$$

$$\mathrm{SC_B} = \mathrm{DSC\_B\_AVE}$$

Thus, the DSC of the sound event within a unit can be calculated as

$$\mathrm{SC_E} = \frac{\mathrm{SC} * 10^{\frac{\mathrm{Leq}}{10}} - \mathrm{DSC\_B\_AVE} * 10^{\frac{\mathrm{Leq\_T}}{10}}}{10^{\frac{\mathrm{Leq}}{10}} - 10^{\frac{\mathrm{Leq\_B}}{10}}}$$

Using a statistical process, the average value and standard deviation of the DSC of all sound events within the clip could be calculated and designated DSC_E_AVE and DSC_E_STD, respectively.

3 Results and discussion

3.1 Perceptual factors of soundscape in urban shopping street

A factor analysis was performed based on all 493 questionnaires collected from the field survey to extract the major perceptual factors of soundscape perception in urban shopping streets. Table 5 shows the result of the varimax-rotated principal component analysis that was used to extract the main factors. The five main factors were identified, including: preference (which explained 16.7% of the variance: beautiful-ugly, relaxing-intense, friendly-unfriendly, harmonious-disharmonious, and like-dislike), communication (which explained 12.6% of the variance: clear-confusing, directional-everywhere, and ordered-disordered), loudness (which explained 12.3% of the variance: strong-weak, light-heavy, quiet-noisy, comfortable-uncomfortable, and lively-depressed), playfulness (which explained 11.6% of the variance: interesting-boring and meaningful-meaningless) and richness (which explained 10.9% of the variance: pure-impure, simple-varied, changing-steady, and lively-depressed). All five main factors that were extracted in this study explained, in total, 64% of the sample variance, which is acceptable considering the complexity of the soundscape evaluation. Meanwhile, the KMO value of the factor analysis was 0.83, which showed that the result could be considered to be quite reasonable and stable. It also should be noted that no significant differences were found between local people, and tourist.

Table 5. Factor analysis of the questionnaire survey, where KMO=0.83 and the variance explained=64%

	Factor				
	1=16.66%	2=12.58%	3=12.3%	4=11.64%	5=10.9%
beautiful-ugly	0.61				
friendly-unfriendly	0.61				
like-dislike	-0.65				
harmonious-disharmonious	0.82				
relaxing-intense	-0.66				
comfortable-uncomfortable			0.59		
light-heavy			0.69		
strong-weak			0.53		
quiet-noisy			-0.71		
lively-depressed			0.54		
changing-steady					0.76
pure-impure					0.73
simple-varied					-0.70
directional-everywhere		0.86			
clear-confusing		0.79			
ordered-disordered		0.60			
interesting-boring				0.83	
meaningful-meaningless				0.86	

The result of the semantic differential analysis shows that there are some similarities and differences between urban shopping streets and other urban spaces. Compared with previous studies on other urban spaces, the major perceptual factors that were extracted are very similar [28, 31, 32] and cover the most basic aspects of an acoustic environment including intensity, content, and variety. However, the analysis also reveals some characteristics of shopping street soundscapes. In this study, each perceptual factor explained approximately 10% to 15% of the total variance, which means that they share similar importance in perception of the soundscape. However, in previous studies, there were several major factors that explained most of the sample variance [45]. This result shows that the soundscape in urban shopping streets is more complex than those of other urban spaces, such as parks, and have more factors with a strong influence on the overall soundscape. However, the result also indicates that more factors can be used to improve soundscape assessment in urban shopping streets. A change in soundscape content is as efficient as controlling the sound level.

3.2 Perceptual factors and common acoustic indicators of sound clips

Figure 5 shows the results of the evaluations of the five perceptual factors in the soundscape clips. The preference, communication and loudness evaluations have very similar patterns, whereas the playfulness and richness evaluations are similar but different from the other three. As shown in Table 4, a higher evaluation value means that the soundscape presented to the subjects incurred a greater level of dislike and was found to be noisier, less playful, more monotonous and harder for communication. It is not surprising that loudness and communication are related because it is certainly difficult to communicate in a very noisy environment. This result shows that the preference of the urban soundscape is also affected by the intensity of the sound environment.

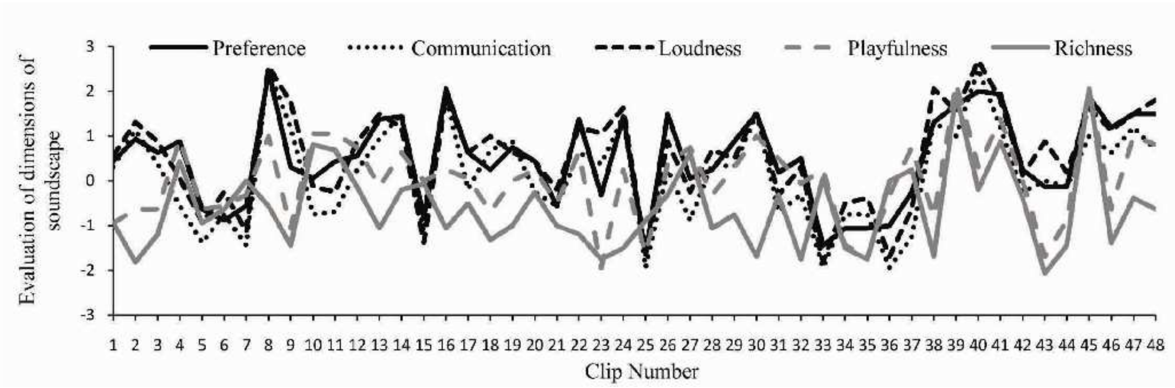

Figure 5. Evaluation of the perceptual factors of the soundscape clips

Figure 6 shows the acoustic indicators of the sound clips used in the laboratory study, including sound level, psychoacoustic and DSC indicators. For sound level, both the equivalent sound level (L_{Aeq} and L_{eq}) and cumulative statistical sound level (L_{10}, L_{50} and L_{90}) were considered, as shown in Figure 6 (A). The A-weighted equivalent sound level of these clips varied from 60 to 80 dBA, which was similar to the sound level range of a real soundscape as measured during the field survey, as shown in Figure 1.

For psychoacoustic indicators, both the average (AVE) and standard deviation (STD) were calculated. Figure 6 (B)-(C) shows that the temporal changes in loudness, sharpness and roughness are quite small (a small standard deviation compared with the mean value), whereas fluctuation strength showed greater variability.

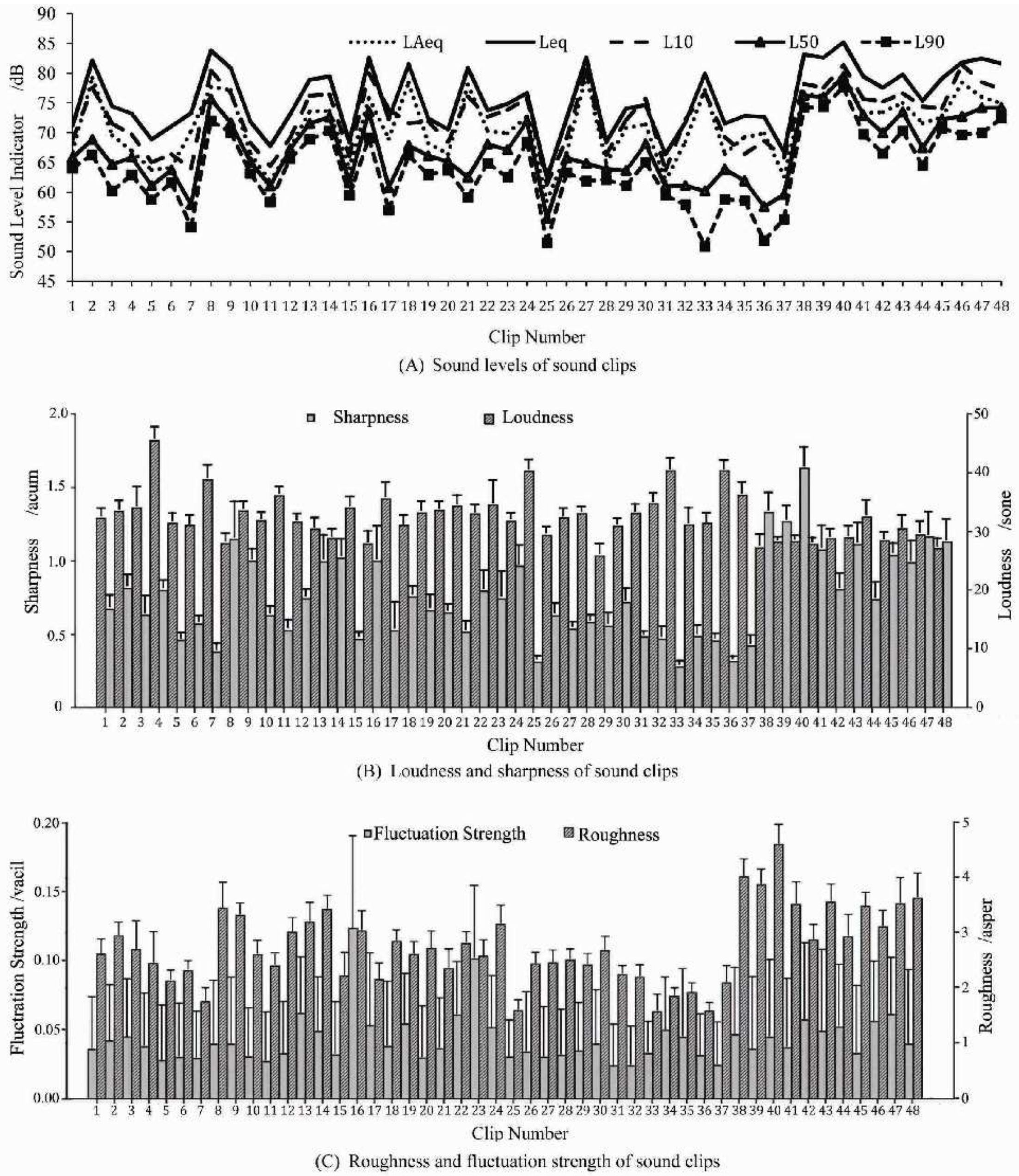

Figure 6. Sound level indicators and psychoacoustic indicators of the recordings, including (A) sound level indicators L_{Aeq}, L_{eq}, L_{10}, L_{50} and L_{90}; (B)-(C) psychoacoustic indicators — (B) loudness and sharpness; (C) roughness and fluctuation strength.

3.3 Correlations between perceptual factors and common acoustic indicators

Table 6 shows the correlations between perceptual factors and acoustic indicators. The situation for three perceptual factors (preference, communication, and loudness) is quite similar. These factors all have significant correlations with sound level, loudness and mean value of sharpness, along with high correlation coefficients. Among all these indicators, the importance of L_{90} can be seen because it has the highest correlation coefficient out of these three perceptual factors, which indicates that they are all greatly affected by the sound level of the background sounds. This conclusion agrees with other previous studies on soundscapes in urban open spaces using field surveys [13]. However, Table 6 also shows that the other two perceptual factors are independent of these indicators. The sound intensity indicators (sound level and loudness) and the indicators that describe subjective sensations (sharpness, roughness, and fluctuation strength) performed poorly in describing the cultural aspects of the soundscape (playfulness and richness). This result shows that the sound level and psychoacoustic indicators alone are unable to describe the overall soundscape, especially in terms of the cultural aspects of the soundscape.

Table6. Correlations between perceptual factors and acoustic indicators, where * means significant correlation ($p<0.05$) and ** means significant correlation ($p<0.01$).

Emotional Factor	Sound Level					Loudness		Sharpness		Roughness		Fluctuation Strength	
	L_{Aeq}	L_{eq}	L_{10}	L_{50}	L_{90}	AVE	STD	AVE	STD	AVE	STD	AVE	STD
Preference	0.45**	0.55**	0.61**	0.79**	0.79**	0.77**	0.71**	0.65**	0.32*	0.78**	0.41**	0.29*	0.47**
Communication	0.57**	0.65**	0.69**	0.87**	0.87**	0.85**	0.76**	0.78**	0.43**	0.84**	0.33*	0.44**	0.58**
Loudness	0.56**	0.66**	0.69**	0.89**	0.90**	0.88**	0.77**	0.82**	0.46**	0.88**	0.36*	0.40**	0.64**
Playfulness	0.09	0.18	0.19	0.27	0.29*	0.27	0.14	0.14	-0.23	0.31*	0.25	-0.22	-0.03
Richness	-0.10	-0.01	-0.10	-0.01	0.01	0.03	-0.16	-0.08	-0.32*	0.06	0.10	-0.36*	-0.10

3.4 Correlation between DSC indicators and perceptual factors

Figure 7 shows the DSC indicators of the clips that were used in the laboratory study, including DSC_E (sound events) and DSC_B (background sounds). In urban shopping streets, the most common background sounds are people talking, advertisements and music, which can be considered continuous mid-frequency sounds. Meanwhile, the sound events in shopping streets vary, including traffic sounds, natural sounds, construction, broadcasting, etc. The result shows that the mean DSC indicator of background sounds is higher than that of sound events, which indicates the higher pitch of background sound. Meanwhile, the standard deviation for sound events is higher than that of background sounds compared with the mean value, which shows a stronger variability of sound events than that for background sounds.

Table 7 shows the correlation between perceptual factors and DSC indicators. The result shows that the DSC (DSC_B_AVE, DSC_E_AVE and DSC_E_STD) indicators are only significantly correlated with two perceptual factors, i.e. playfulness and richness. The evaluation values of playfulness and richness (higher evaluation values means less playful and more monotonous) increase with decreasing DSC_B_AVE, DSC_E_AVE and DSC_E_STD. According to the concept shown in Section 3.4.1, DSC_B_AVE, DSC_E_AVE and DSC_E_STD described the mean timbre sensation of background sounds, the mean timbre sensation of sounds events and the fluctuation strength of sound events, respectively. The result of the correlation analysis indicates that a higher pitch of background sounds, a higher pitch of sound events and more variety of sound events will lead to a more playful and rich soundscape in urban shopping streets.

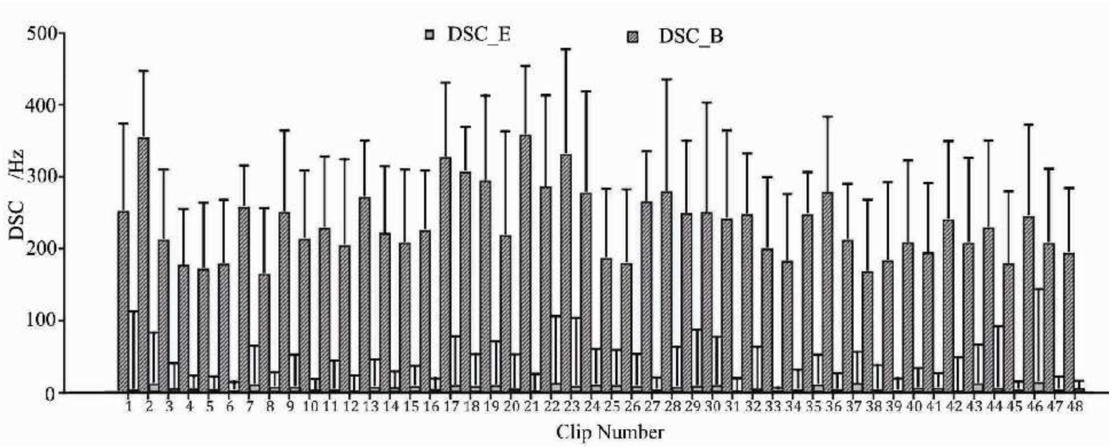

Figure 7. DSC indicators of the recordings, where DSC_E is the DSC indicator of a sound event and DSC_E is the DSC indicator of background sounds.

The result of the correlation analysis shows the capability of the DSC analysis in terms of describing the subjective response to the cultural aspects of the urban soundscape. However, it should be noted that the correlation coefficients between DSC indicators and perceptual factors are small when compared with those between sound level and perceptual factor, although the correlations are statistically significant. There are many reasons for this. First, there are inevitable differences among the subjects that will decrease the correlation coefficient. More importantly, the DSC indicators considered only the spectral information, which cannot describe all of the sound source information. There are many other factors that will also affect the evaluation of soundscapes, such as spatial factors.

Table 7. Correlations between perceptual factors and acoustic indicators, where * denotes a significant correlation (p<0.05) and ** denotes a significant correlation (p<0.01).

Emotional Factors	DSC_B		DSC_E	
	AVE	STD	AVE	STD
Preference	-0.11	0.17	0.05	0.01
Communication	0.02	0.26	0.12	0.10
Loudness	-0.01	0.25	0.10	0.10
Playfulness	-0.29*	-0.01	-0.30*	-0.42**
Richness	-0.38**	-0.20	-0.42**	-0.52**

The results of this study could lead to some practical rules for policy making, planning design, and soundscape practices in urban shopping streets.

(1) Various methods can be used to improve urban shopping street soundscapes. In most cases, the sound levels of most sound sources are hardly controllable—for example, people talking. However, it is still possible to satisfy the public by adding more pleasant, interesting sound events and removing unpleasant events without controlling the

majority of the background sounds. Generally speaking, non-artificially generated sounds, especially natural elements were usually considered as pleasant and have positive effect on the overall soundscape. [46] Kang has suggested music and water sound can improve acoustic comfort as a pleasant sound source.[11] Jeon et al. has also showed the effect of water sound on masking traffic noise, which also could improve the overall soundscape evaluation[41].

(2) Soundscape evaluation can be improved through planning treatment. The analysis of this study shows that sound intensity mainly affects the functional aspects—for instance, the degree of loudness and communication perception—whereas the composition of the sound environment affects the cultural aspects. Therefore, in the relaxation and dining areas where more private conversations occur, controlling the sound level should be the major goal for soundscape design. However, in other areas, such as shopping and tourist areas, it might be good to add some designed sounds, such as music, even though this may increase the overall sound level.

4 Conclusions

The perceptual and physical features of soundscapes in urban shopping streets have been investigated using a field survey and a laboratory study, which produced the following observations:

Five major perceptual factors have been identified using the semantic differential method, including preference, loudness, communication, playfulness and richness. The five major perceptual factors of this study explained a total of 64% of the sample variance, and each factor shows very similar importance (which accounted for approximately 10% to 15% of the variance) in representing the overall soundscape. This result shows that soundscapes in urban shopping streets are more complex than those in other urban spaces—such as parks—and more factors have a strong influence on the overall soundscape.

Sound level and psychoacoustic indicators have been found to be efficient in describing the functional aspects of soundscape perception, including preference, loudness, and communication. Among all sound level and psychoacoustic indicators, L_{90} has the strongest correlations with perceptual factors, which showed that the intensity of background sounds had a significant influence on the evaluation of soundscapes in urban shopping streets. A lower background sound level (lower L_{90}) may foster a sense of quiet, likeability and ease of communication with others.

A new method (DSC) was developed in this study on the basis of the concept of spectrum gravity centre and temporal variety analysis. The DSC analysis combined spectral and temporal analysis to describe the content of background sounds and sound events. The DSC indicators were found to have a significant correlation with two perceptual factors (playfulness and richness), which cannot be described well by sound level and psychoacoustic indicators. Increasing the variability of sound events (higher standard deviation of DSC_E) could make the soundscape more playful and richer.

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