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Linear multivariate evaluation models for spatial perception of soundscape

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ABSTRACT: Soundscape is a sound environment that emphasizes the awareness of auditory perception and social or cultural understandings. The case of spatial perception is significant to soundscape. However, previous studies on the auditory spatial perception of the soundscape environment have been limited. Based on 21 native binaural-recorded soundscape samples and a set of auditory experiments for subjective spatial perception (SSP), a study of the analysis among semantic parameters, the inter-aural-cross-correlation coefficient (IACC), A-weighted-equal sound-pressure-level (L_{eq}), dynamic (D) and SSP is introduced to verify the independent effect of each parameter and to re-determine some of their possible relationships. The results show that the more noisiness the audience perceived, the worse spatial awareness they received, while the closer and more directional the sound source image variations, dynamics and numbers of sound sources in the soundscape are, the better the spatial awareness would be. Thus, the sensations of roughness, sound intensity, transient dynamic and the values of L_{eq} and IACC have a suitable range for better spatial perception. A better spatial awareness seems to promote the preference slightly for the audience. Finally, setting SSPs as functions of the semantic parameters and L_{eq}-D-IACC, two linear multivariate evaluation models of subjective spatial perception are proposed.

Keywords: Spatial perception, Binaural-recorded, IACC, Semantic parameter

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1. Introduction

Soundscape, which was previously proposed by Canadian composer and ecologist Schafer in the 1970s, is a sound environment that emphasizes human awareness of their auditory perceptions or social and cultural understandings. Soundscape, as defined by Schafer, includes three main factors: audience, environment and a sound event with the features of keynote, sound signal and soundmark [1].

In the case of human awareness, sound spatial perceptions are defined as a general auditory awareness of the three-dimensional sound spaces, locations and variations [2]. Because soundscape cannot be isolated from the landscape [3, 4], it is always significant to

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soundscape. During the 1950s, inter-aural level difference (ILD) and inter-aural time difference (ITD) were mechanisms for sound localizations [5, 6], and then binaural impulse response was proposed by Schroeder [7] to examine the sound quality of room acoustics. With the development of binaural recording technology, the inter-aural cross-correlation coefficient (IACC) was suggested as an independent acoustic parameter to evaluate sound spatial perceptions of a concert hall [2], and some relationships between room acoustics and psychoacoustics were found based on further study of the IACC [8, 9]. Around 2000, still based on the IACC, a model of the auditory brain system proposed by Ando was suggested to describe the primitive temporal and spatial factors for some spatial sensations, such as localization in the horizontal plane of sound fields [10, 11, 12]. Recently, the head-related transfer function (HRTF) and inter-aural cross-correlation function (IACF) were used to create the spatial awareness of virtual audio environments and sound playback systems [13, 14, 15]. However, previous studies on sound spatial perception of open space and soundscape environments were limited, and few efficient predictive models were introduced. According to some of the newest studies regarding the spatiotemporal variability of soundscapes [16], soundwalk [17], listening behaviors in public space [18, 19] and the evaluations of acoustic and cultural awareness for historical soundscape environments [20, 21, 22], physical acoustic parameters alone, such as A-weighted equal sound pressure level (L_{eq}), IACC or dynamic (D) defined as the maximum difference of sound pressure level during the amplitude variations of a sound signal [21], are not efficient for predicting a more complicated spatial perception of the soundscape or real urban and rural public sound space.

Thus, based on 21 typical native binaural-recorded soundscape samples and a set of auditory experiments for the subjective spatial perceptions, the aim of this study is to verify the independent effect on subjective spatial perceptions (SSPs) of semantic parameters and three well-known and simple-measured acoustic parameters, IACC, L_{eq} (dBA) and D (dynamic); re-determine some of their possible relationships; and finally propose two linear multivariate evaluation models of subjective spatial perceptions, taking into account SSPs as functions of the semantic parameters and L_{eq}-D-IACC.

2. Methods

2.1 Study areas and samples

The study was conducted in the Guangxi Province in the southern China, which is an ethnically diverse region with many types of unique but typical soundscape ecologies and cultures. The 21 binaural-recorded soundscape samples were recorded at three different historical autonomous areas of Zhuang Nationality, as shown in Fig. 1, including the central areas of Liuzhou City, Longji Village of Longsheng County, and Mudu Village of Napo County. The descriptions of soundscape contents and original occurrence circumstances are listed in TABLE II, with their sound level envelopes shown in Fig. 2.

1a. Soundscape sample 1 - 6 from the central areas of Liuzhou City
1b. Soundscape sample 7 - 18 from Mudu Village
1c. Soundscape sample 19 - 21 from Longji Village

1d. Sample 1 1e. Sample 2 1f. Sample 3 1g. Sample 4 1h. Sample 5 1i. Sample 6

1j. Sample 7 1k. Sample 8 1l. Sample 9/10 1m. Sample 11/15 1n. Sample 12 1o. Sample 13/14

1p. Sample16 1q. Sample 17 1r. Sample 18 1s. Sample 19 1t. Sample 20 1u. Sample 21

Fig. 1. The native locations and situations of 21 soundscape samples

2.2 Binaural recording technology

The binaural-recorded signals typically come from two small omni-directional microphones, which are located in the ear canal of a human head or dummy head. When played through a pair of stereo earphones or headphones, a binaural-recorded sound signal could represent the spatial information around the head of the audience, mainly including the sound image locations and their variations with SPL variations. Binaural recording technology was previously used to examine the binaural impulse response of room acoustics[6]. It is easy to acquire another important acoustic parameter, IACC, from binaural-recorded samples by using Equation (1), while the IACF can be acquired as shown in Equation (2).

All samples used in this paper were collected using binaural recording technology with the same real human head, and all samples were binaural sounds (3D sounds) based on the characteristics of the human auditory system. In order to avoid the effect on IACC evaluation from the movement of head, the positive axis of the human head was kept to a fixed direction as far as possible for stationary recorded samples, and for the sound walking samples, it was kept along with the forward direction of the walking path. The fixed directions of the stationary samples and walking paths of the sound walking samples were based on the situation of environment and the recommendation of local people. The “stationary” or “sound walking” status of each sample is listed in the last column of Table 2.

In this paper, all of the binaural-recorded samples are digitized with a 44.1 kHz sampling rate. Due to the possible maximum distance of the two eardrums, the delay time between the two eardrums is in the range of -44 samples to 44 samples because the aural sound images on the left and right hemispheres are approximately symmetric, especially in the middle frequency and low frequency[8]. The delay time τ, represented by the sample numbers, should be set in a range of 0 to 44 samples. Then, according to Equation (2), the variegated IACF curves of the 21 samples are shown normally in Fig. 3.

$$\mathrm{IACC} = \max\left|\mathrm{IACF}_{t_1 t_2}(\tau)\right| \tag{1}$$

$$\mathrm{IACF}_{t_1 t_2}(\tau) = \frac{\int_{t_1}^{t_2} p_L(t)\, p_R(t+\tau)\,dt}{\sqrt{\int_{t_1}^{t_2} p_L^2(t)\,dt \cdot \int_{t_1}^{t_2} p_R^2(t)\,dt}} \tag{2}$$

- p_L, the sound pressure received by the left ear, represented by the voltage level of the left channel;

- p_R, the sound pressure received by the right ear, represented by the voltage level of the right channel;

- τ, the delay time between two ears, represented by the sample numbers in a digitalized sound signal.

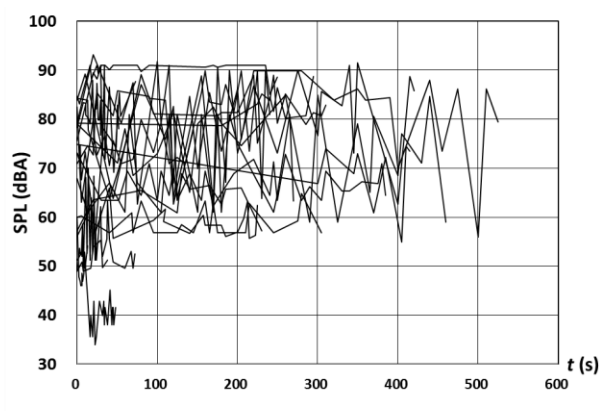


Fig. 2. Sound pressure level envelopes of samples

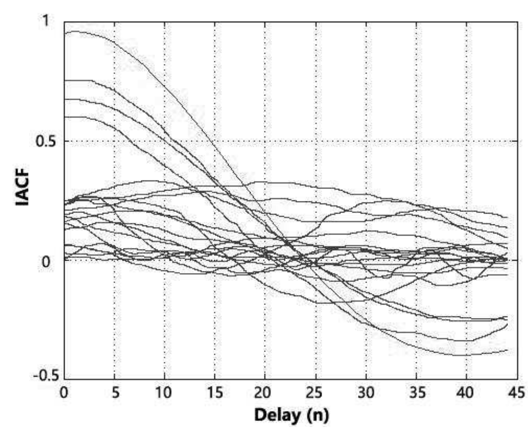


Fig. 3. IACF curves of samples

2.3 Auditory experiment and semantic parameters

To perceive the psychoacoustic sensations related to subjective spatial perceptions of normal people, an auditory experiment for all of the above 21 samples based on the semantic differential method [23] was designed in this study. Twelve male and twelve female non-local subjects with normal hearing ability and from 20 to 40 years old were asked to complete a semantic measurement questionnaire with a 5-point Likert scale of the 11 pairs of semantic parameters, as shown in Table 1. All of the subjects were well trained to understand the correct meanings of all semantic pairs.

Table 1. Semantic parameters measurement questionnaire

No.	Semantic parameter and code	5-point Likert scale				
		-2	**-1**	**0**	**1**	**2**
1	**QN** (Quiet – Noisy) **BL** (Boring – Lively) **RS** (Rough – Smooth) **DO** (Directive – Omni) **CF** (Close – Far) **WS** (Weak – Strong) **SIV** (Sound image variation, Less - More) **TrD** (Transient Dynamic, Low - High) **NSS** (Number of sound sources, Less - More) **SPA** (Subjective preferred assessment, Don't like - Like) **SSP** (Subjective spatial perceptions, Low – High)					

All samples were binaural-recorded sounds and played back through a standard stereo headphone system with sound pressure levels consistent with the values of L_{eq} in TABLE II and an interval of 10 s between each sound. The duration of each soundscape sample was from 26 s to 239 s.

2.4 Statistical analysis

Pearson correlation analysis was used to examine the possible relationships among the semantic parameters, IACC, L_{eq} (dBA), D (dynamic) and the SSP. Then, the SSP was set as the controlling variable, and principal components analysis and system clustering analysis were applied to determine the interaction influence of QN, BL, RS, DO, CF, WS, SIV, TrD, NSS and SPA, as well as to find the orthogonal principal components of the SSP. Finally, multi-regression was used to create the linear single-value evaluation models of the SSP. All of the statistics mentioned above were carried out in MATLAB® 2012a, SPSS® 20.0 and Excel® 2013.

3. Results, Analysis and Models

3.1 Correlation analysis

According to the results of the auditory experiment, the average values of the semantic parameters (QN, BL, RS, DO, CF, WS, SIV, NSS, SPA and the SSP), IACC, L_{eq} and descriptions of the soundscape contents are shown in Table 2. The correlations are shown in Table 3.

Generally, the sensation of sound directivity (DO) has the highest correlation with the subjective spatial perception (SSP), with a negative coefficient of -0.660, while the sensation of sound distance (CF) also has an approximate negative correlation but with a smaller absolute value of the coefficient of -0.252. The sensations of sound source image variations and numbers (SIV and NSS) have a positive correlation with the SSP, with coefficients of 0.552 and 0.561, respectively. The sensations of sound intensity (QN with a coefficient of 0.355, WS with a coefficient of 0.316 and TrD with a coefficient of 0.373) have weaker but detectable positive correlations, while the sensation of roughness (RS) has a weaker but negative correlation of -0.348. Finally, the overall sensation of preference (BL and SPA) has the lowest correlation with the subjective spatial perception (SSP), i.e., 0.019 and 0.006, respectively, which are close to zero. Moreover, in the cases of the three important acoustic parameters, i.e., IACC, L_{eq} and D (dynamic), the highest correlation value (i.e., 0.621) exists between D (dynamic) and SSP, while the other ones show a similarity for the absolute values of -0.193 and 0.205.

Table 2. Semantic and acoustic parameter values of the soundscape samples

No.	**Average value of semantic parameters**											**Acoustic**			**Soundscape description**	**Status of recorded position**
	QN	BL	RS	DO	CF	WS	SIV	TrD	NSS	SPA	SSP	IACC	L_{eq} (dBA)	D (dB)		
1	0.54	0.92	0.00	-0.29	0.00	-0.21	1.29	0.17	0.71	0.75	0.75	0.22	65	37	Tango in Liuhou Park.	Stationary
2	1.46	-0.63	-0.83	0.33	-0.83	0.88	0.29	0.83	0.63	-0.83	-0.83	0.18	65	33	Elderly people activities.	Stationary
3	1.67	-0.33	-0.50	-0.42	-0.71	0.88	0.96	0.71	0.71	-0.38	-0.38	0.09	73	26	Guangming Road Market.	Sound walking
4	1.38	-0.21	-0.29	-0.33	-0.79	0.88	0.79	0.58	0.21	-0.46	-0.46	0.31	74	27	Yu-ma Park soundscape.	Sound walking
5	0.79	0.29	0.08	0.17	-1.04	0.83	-0.21	0.50	-0.04	0.00	0.00	0.26	85	5	Small folk orchestra with	Stationary
6	0.38	0.54	0.00	-0.04	-0.83	0.54	0.50	0.63	0.75	0.17	0.17	0.23	75	31	Three antiphonal singing.	Stationary
7	-0.42	1.38	0.79	-0.71	-0.75	0.08	1.04	0.63	0.54	1.21	1.21	0.14	72	46	Village dusk soundscape.	Sound walking
8	-1.17	0.54	0.63	-0.33	-0.17	-0.71	-0.21	-0.25	-0.50	0.13	0.13	0.27	55	36	Village night soundscape.	Sound walking
9	-1.38	0.63	0.75	-0.04	-0.08	-0.50	0.13	-0.33	0.17	0.33	0.33	0.33	60	35	Village morning, sound.	Sound walking
10	-1.71	0.67	1.13	1.00	0.79	-1.29	-1.04	-0.96	-0.33	0.54	0.54	0.05	40	11	Village morning, quiet.	Sound walking
11	-1.38	0.46	0.71	0.54	0.50	-0.92	-1.04	-0.71	-0.58	0.29	0.29	0.04	48	9	Village sound with insects.	Stationary
12	-0.88	0.42	0.25	0.04	-0.67	-0.63	-0.38	-0.29	-0.25	0.25	0.25	0.12	55	25	Village sound of working.	Sound walking
13	-1.21	0.17	0.25	0.25	-0.67	0.13	-0.25	0.46	0.25	0.54	0.54	0.96	75	46	Talk among local people.	Stationary
14	-0.38	0.38	0.33	0.29	-0.58	-0.33	-0.46	0.13	-0.46	0.13	0.13	0.60	69	12	Village sound in farmland.	Sound walking
15	-0.29	0.42	-0.08	0.58	-0.92	0.13	-0.38	0.33	0.08	0.13	0.13	0.67	75	37	Village sound with birds.	Stationary
16	0.00	0.75	0.29	0.58	-1.38	0.67	0.17	0.67	-0.04	0.58	0.58	0.76	76	13	Village sound with crowing.	Sound walking
17	0.25	0.46	0.38	0.17	-1.21	0.75	-0.67	0.54	-0.13	0.38	0.38	0.22	79	21	Antiphonal singing.	Stationary
18	0.75	0.33	-0.29	-0.50	-1.42	1.04	0.63	0.63	0.75	0.04	0.04	0.15	70	52	Interviews for the singers.	Stationary
19	-0.75	-0.04	0.25	-0.04	0.04	-0.71	-0.29	-0.50	-0.04	-0.21	-0.21	0.27	50	17	Village soundscape indoors.	Stationary
20	0.63	-0.63	-0.29	0.00	-0.42	0.38	0.54	0.33	0.38	-0.54	-0.54	0.59	70	35	Valley sound walking.	Sound walking
21	-0.67	0.58	0.13	-0.29	-0.50	-0.04	0.21	-0.08	-0.04	0.42	0.42	0.05	57	33	Village sound walking.	Sound walking

Table 3. Correlation coefficients among the subjective spatial perception parameters

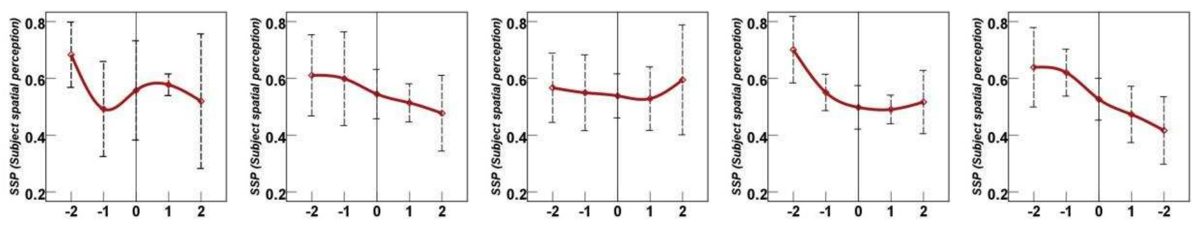
Parameters	QN	BL	RS	DO	CF	WS	SIV	TrD	NSS	IACC	L_{eq} (dBA)	D	SPA	SSP
NQ	1													
BL	-0.517	1												
RS	-0.857	0.714	1											
DO	-0.357	-0.058	0.260	1										
CF	-0.593	0.107	0.536	0.265	1									
WS	0.861	-0.370	-0.744	-0.314	-0.854	1								
SIV	0.643	-0.047	-0.523	-0.750	-0.344	0.538	1							
TrD	0.794	-0.234	-0.682	-0.350	-0.859	0.935	0.613	1						
NSS	0.656	-0.181	-0.620	-0.504	-0.394	0.631	0.832	0.674	1					
IACC	-0.071	-0.129	-0.088	0.301	-0.310	0.161	-0.067	0.295	-0.039	1				
L_{eq} (dBA)	0.638	-0.107	-0.478	-0.223	-0.834	0.845	0.415	0.890	0.458	0.452	1			
D (dB)	0.109	0.053	-0.268	-0.583	-0.261	0.244	0.568	0.366	0.622	0.122	0.184	1		
SPA	-0.564	0.939	0.721	-0.010	0.130	-0.370	-0.062	-0.212	-0.150	0.018	-0.079	0.106	1	
SSP	0.355	0.006	-0.348	-0.660	-0.252	0.316	0.552	0.373	0.561	-0.193	0.205	0.621	0.019	1

3.2 Independent effect

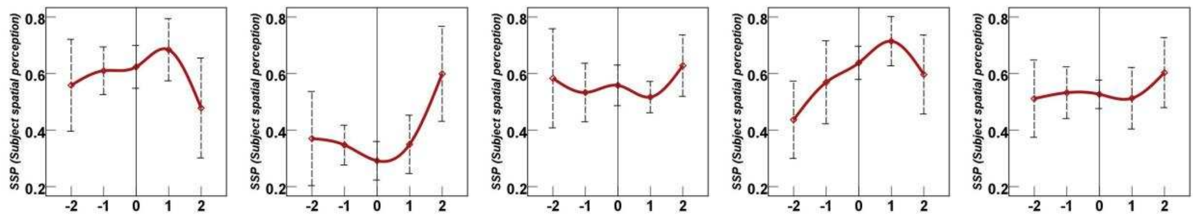
1. Independent effect of semantic parameter

Based on the 5-point Likert scale, an analysis with standard deviations for the variations of the SSP against the semantic parameters is shown in Fig. 4. According to the linked curves of the average values of the SSP, the independent effect of a semantic parameter can be interpreted in more detail.

Fig. 4a shows an overall decline in relations between the sensation of noisiness (represented by QN, one of the parameters related to the sensation of sound intensity) and the subjective spatial perception (SSP). Namely, the more noise the audience hears, the worse their perceived spatial awareness becomes. According to Fig. 4d and 4e, the sensations of sound directivity (DO) and sound distance (CF) have similar monotonically decreasing relationships with the subjective spatial perception (SSP). It is interesting to note that a close soundscape could result in a relatively high spatial perception, while it is easy to understand that directive sounds could create a more spatial sound environment. As shown in Fig. 4b, there is also a monotonically decreasing but weaker relationship between the parameters BL and SSP.



4a. QN, STD = 0.070 4b. BL, STD = 0.057 4c. RS, STD = 0.029 4d. DO, STD = 0.087 4e. CF, STD = 0.075



4f. WS, STD = 0.079 4g. SIV, STD = 0.120 4h. TrD, STD = 0.043 4i. NSS, STD = 0.104 4j. SPA, STD = 0.050

Fig. 4. Independent effect of semantic parameters with the standard deviations (STD)

In contrast, Fig. 4g, 4i and 4j give the overall increasing relationships among the sensations of sound source image variations (SIV), numbers of sound sources (NSS) and subjective preferred assessment (SPA) and the subjective spatial perception (SSP), which means that more variations and numbers of sound sources may help people to increase their spatial awareness of the soundscape environments; moreover, according to Fig. 4j, people appear to prefer to like the soundscape with a little bit more spatial perception even though the feelings of boredom or liveliness for the soundscape (represented by BL, another parameter related to the overall sensation of preference) have a slight monotonically decreasing relationship with the SSP.

However, for the independent effects from the sensations of roughness (RS), sound intensity represented by WS, and transient dynamic (TrD, another parameter related to sound intensity), the situations are more complex. According to Fig. 4c and 4h, both the extreme sensations of roughness and dynamic variations of sounds may slightly benefit the subjective spatial perception (SSP), while on the contrary, either too much weak or strong sound may result in a slight aggression in relation to the spatial awareness, as shown in Fig. 4f, which means that it must be an important cue to find an optimal range of sound intensity awareness for a better subjective spatial perception. This will be discussed further in Section 3.2.2, when introducing the independent effect of L_{eq}.

2. Effect of L_{eq}

The acoustic parameter L_{eq} is always a critical and positive factor for many auditory sensations of the sound environment, including loudness, noisiness, roughness, pleasance and, of course, the spatial awareness[4, 8]. However, based on the results of this study, several differences are apparent: first, there is a relatively lower correlation coefficient (i.e., 0.205) between L_{eq} and SSP, as listed in TABLE III; second, there is a range of L_{eq} corresponding to the best SSP due to the shape of the cubic polynomial fitting curve of Fig. 5. For example, sample 18 has the highest SSP value but not the highest L_{eq} value. This is consistent with the relationship between the parameter WS and SSP of Fig. 4f and contrary to the non-monotonic relationship between the parameter RS and SSP of Fig. 4f.

According to the correlation coefficients in Table 3, the sensations of noisiness (QN), roughness (RS), sound source distance (CF), weakness (WS) or variations of sound pressure levels (TrD) are highly correlated with the L_{eq} values; normally, they also have similar non-monotonic relationships with the SSP. However, in addition to the parameters WS and RS, the other parameters have monotonic relationships with the SSP. Namely, the sensation for sound intensity of a real changeable soundscape environment is not exactly equal to the physical sound level.

3. Effect of dynamic

According to Table 3, parameter D has the highest positive correlation coefficient (0.621) of the acoustic parameters, and its nearly monotonically increasing relationship with the SSP is shown in Fig. 6. This is similar to the sensations of sound source image variations (SIV) and numbers of sound sources (NSS) shown in Fig. 4g and 4j, respectively, but with very different from the transient dynamic sensation (TrD) shown in Fig. 4h. Namely, the sensation for dynamic changes of a real changeable soundscape environment is not exactly equal to the physical sound dynamic.

4. Effect of IACC

Another important acoustic parameter related to spatial awareness is IACC, and some models based on IACC have suggested that if the value of IACC is close to zero, this means that the sounds for two ears are uncorrelated and full of spatial perceptions. On the contrary, when the sound in the middle of two ears brings identical sound pressures on both ears, then the value of IACC is 1, which indicates no sense of spatial perceptions[5]. However, similar to the effect of L_{eq}, there is a correlation coefficient of only -0.193 between IACC and the SSP, as listed in Table 3, and excluding samples 5, 9, 10 and 13, there is also a range of low IACC values corresponding to the best SSP, as shown in Fig. 7.

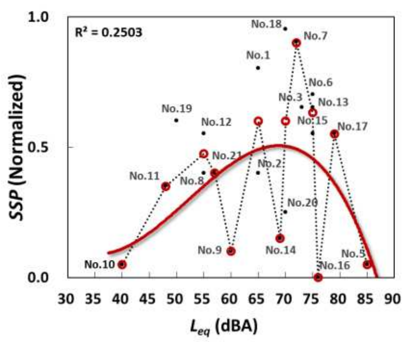


Fig. 5 Relationship between L_{eq} and SSP, with a range of moderate L_{eq} values corresponding to the best SSP

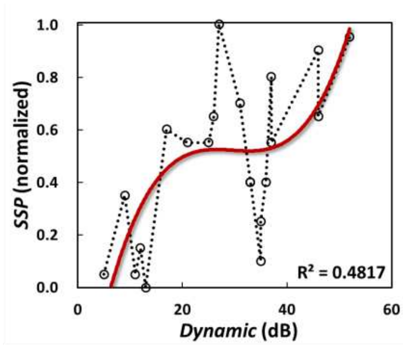


Fig. 6 A nearly monotonically increasing relationship between dynamic (D) and SSP

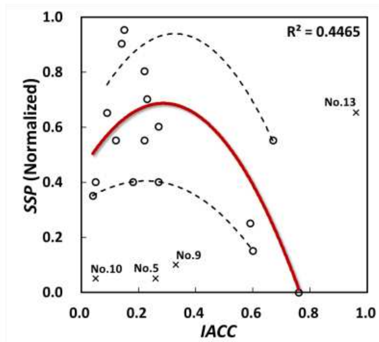


Fig. 7 Relationship between IACC and SSP, with a range of low IACC values corresponding to the best SSP

3.3 Inter-relationships

1. Principal components and clusters

Because the spatial awareness for soundscapes in real rural or urban environments is highly dynamic and depends significantly on multivariate sensations as mentioned above, principal component analysis (PCA) and hierarchical clustering analysis (HCA) will be introduced in this section to determine some possible main components and perception models of the subjective spatial perceptions (SSP). Setting the SSP as the controlling variable, based on the average values of the semantic parameters QN, BL, RS, DO, CF, WS, SIV, TrD, NSS and SPA, the PCA results are shown in Fig. 8 and Table 4, with the eigenroots [2.388, 1.458, 1.082] of the principal components vector [C1, C2, C3]. To verify the distributions of semantic parameters, HCA results are shown in Table 5. Methodologically, these two methods have a reciprocal authentication to each other, and give more confidence to extract the perception modes of SSP.

Table 4. Results of PCA

Semantic Parameters	Weight Order	Total Weight*	Component coefficients**		
			C1	C2	C3
QN	4	0.131	0.391	-0.076	-0.008
BL	10	0.001	-0.212	0.555	0.179
RS	7	0.106	-0.374	0.229	0.074
DO	8	0.075	-0.201	-0.362	0.452
CF	3	0.135	-0.301	-0.132	-0.552
WS	2	0.151	0.385	0.029	0.311
SIV	6	0.119	0.304	0.335	-0.391
TrD	1	0.158	0.373	0.145	0.317
NSS	5	0.122	0.325	0.222	-0.256
SPA	9	0.002	-0.216	0.550	0.194

*Normalized weight coefficients, the total summation is standardized to 1, and only the first three principal components are used to calculate the total weight of each component.

**Kaiser-Meyer-Okin measure of sampling adequacy, 0.719; cumulative 90.013%; extraction method, principal component analysis. The component coefficients are calculated by using component matrix values divided by the eigenroot of the corresponding principal component.

Table 5. HCA results and their membership parameters

Clustering distance algorithm	Minimum rescaled distance	Cluster and membership parameters		
		1	2	3
Euclidean	15	SPA BL RS	DO CF	SIV NSS WS TrD QN
Pearson	13	SPA BL RS	DO CF	SIV NSS WS TrD QN
Chebychev	23	SPA BL RS CF	DO	SIV NSS WS TrD QN
Minkowski	16	SPA BL RS	DO CF	SIV NSS WS TrD QN

2. Perception modes of SSP

According to the minimum rescaled distances of some normal clustering distance algorithms in Table 5 and the effective component matrix values in Table 6, the optimal clusters and their corresponding SSP semantic modes with semantic parameters are shown in TABLE VI, while the Pearson clustering dendrogram is shown in Fig. 9.

Table 6. Optimal clusters and the corresponding modes of SSP with semantic parameters

Cluster	Mode	Semantic
1	**SI mode** (based on the parameters related to sound intensity and its variations)	SIV, NSS, WS, TrD, QN
2	**SC mode** (based on the parameters related to sound contents)	SPA, BL, RS
3	**SD mode** (based on the parameters related to sound directivity)	DO, CF

Combining the HCA results of TABLE VI with the PCA coefficients of TABLE IV, it can be suggested that: the principal component C1, with a total weight of 0.634, is equivalent to the SI mode related to sound intensity and its variation and mainly dependent on the parameters SIV, NSS, WS, TrD, QN and L_{eq}; C2, with a total weight of 0.236, is equivalent to the SC mode related to sound contents and mainly dependent on the parameters SPA, BL and RS; and C3, with a total weight of 0.130, is equivalent to the SD mode related to sound directivity and mainly dependent on the parameters DO, CF and IACC. Thus, the component values of the three SSP modes can be represented by Equations (3) to (5), in which of the SSP_{SI}, SSP_{SC} and SSP_{SD} are defined as the new semantic components related to the perceptions of sound intensity and its variations (SI mode), sound contents (SC mode) and sound directivity (SD mode) respectively.

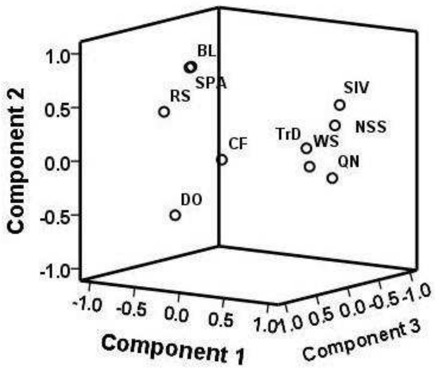


Fig. 8. Dimensions of PCA and the distributions of semantic parameters

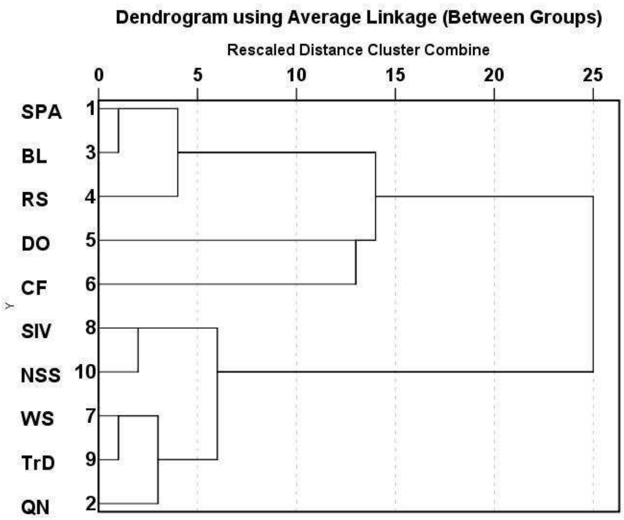


Fig. 9. HCA dendrogram of semantic parameters, Pearson correlation method

$$SSP_{SI} \sim C1 = 0.391QN - 0.212BL - 0.374RS - 0.201DO - 0.301CF + 0.385WS + 0.304SIV + 0.373TrD + 0.325NSS - 0.216SPA \quad (3)$$

$$SSP_{SC} \sim C2 = -0.076QN + 0.555BL + 0.229RS - 0.362DO - 0.132CF + 0.029WS + 0.335SIV + 0.145TrD + 0.222NSS + 0.550SPA \quad (4)$$

$$SSP_{SI} \sim C3 = -0.008QN + 0.179BL + 0.074RS + 0.452DO - 0.552CF + 0.311WS - 0.391SIV + 0.317TrD - 0.256NSS + 0.194SPA \quad (5)$$

3.4 Linear single-value evaluation model

1. Semantic model

Based on the average values of Table 2 and Equations (3) to (5), values of the components SSP_{SI}, SSP_{SC} and SSP_{SD} for all samples are shown in Fig. 10.

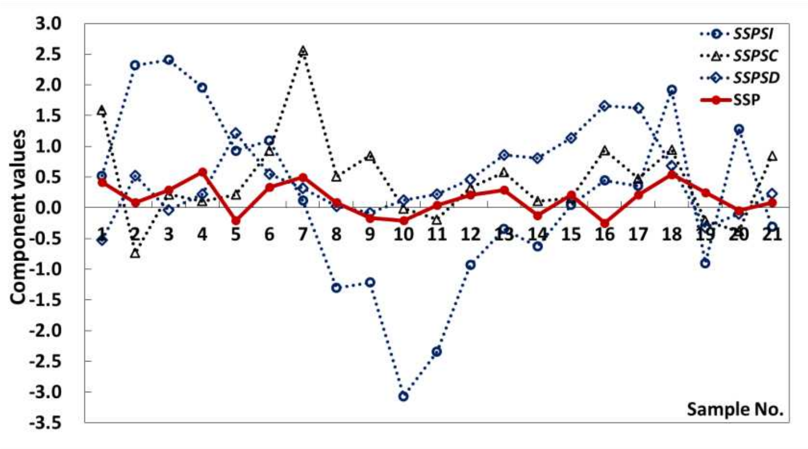


Fig. 10. Comparisons among SSP_{SI}, SSP_{SC}, SSP_{SD} and the SSP values of Table 2

According to the algorithm of principal components analysis, the components extracted are orthogonal to each other. Thus, a linear single-value semantic regression model of the SSP can be approximated by Equation (6) with the multi-regression coefficients in Table 7.

$$SSP = 0.082 \cdot SSP_{SI} + 0.130 \cdot SSP_{SC} - 0.128 SSP_{SD} + 0.136 \tag{6}$$

Equation (6) has already shown that the semantic parameters of evaluation are simplified to the three components corresponding to Equation (3), (4) and (5). If the assessments of the sensations of sound intensity, sound content and sound directivity are known, then the subjective spatial perception (SSP) of a binaural-recorded soundscape sample is easy to predict.

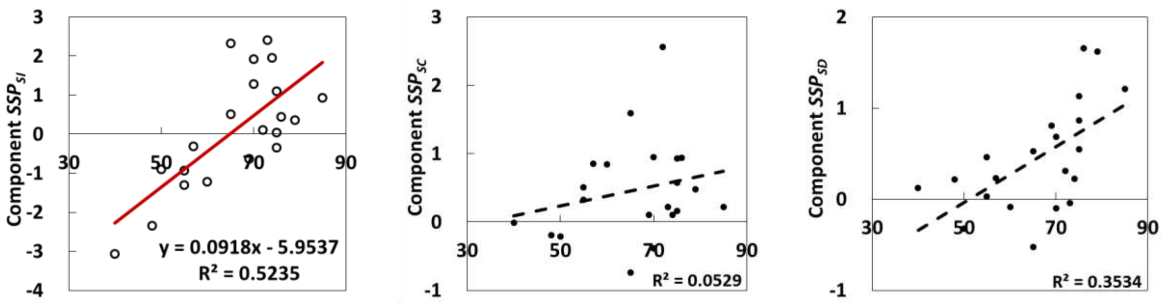
Table 7. Regression among the new semantic components and SSP

Predictors	**Coefficients**	**t**	**Sig.**
(Constant)	0.136	2.053	0.056
SSP_{SI}	0.082	2.541	0.021
SSP_{SC}	0.130	1.982	0.064
SSP_{SD}	-0.128	-1.589	0.130

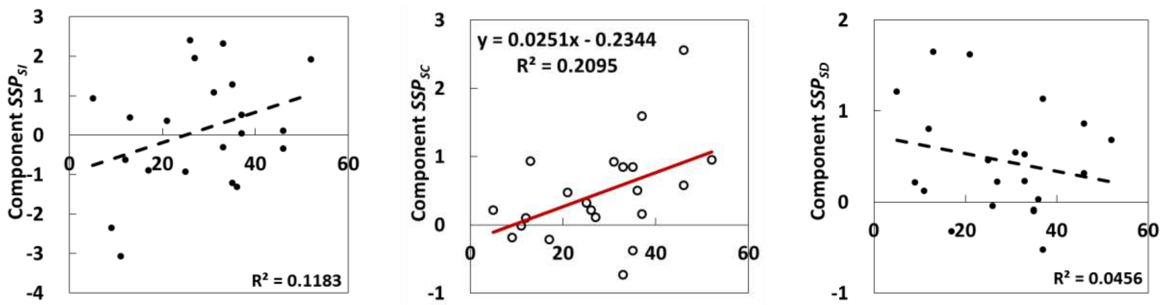
2. Acoustic model

According to linear fitting analysis, some linear regression relationships either between L_{eq} and SSP_{SI}, D (dynamic) and SSP_{SC}, or IACC and SSP_{SD} can be found in Fig. 11.

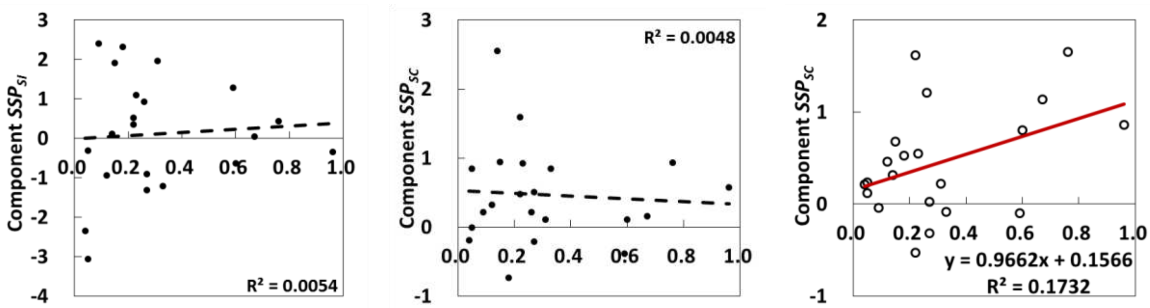
Applying the regression formulas of Fig. 11 to Equation (6), the linear single-value semantic regression model of the SSP, represented by the parameters L_{eq}, D (dynamic) and IACC, can be approximated by Equation (7), which means that for a binaural-recorded soundscape sample, the value of the SSP can be predicted just by use its corresponding values of L_{eq}, D (dynamic) and IACC with a known awareness of sound contents.



11a. L_{eq} (dBA) vs. SSP_{SI}, SSP_{SC} and SSP_{SD}



11b. Dynamic (dB) vs. SSP_{SI}, SSP_{SC} and SSP_{SD}



11c. IACC vs. SSP_{SI}, SSP_{SC} and SSP_{SD}

Fig. 11. Linear relationships between semantic components and acoustic parameters, with the squared correlations and the solid lines suggesting the regression formula

$$\begin{aligned}
SSP &= 0.082 \cdot SSP_{SI} + 0.130 \cdot SSP_{SC} - 0.128 SSP_{SD} + 0.136 \\
&= 0.082(0.0918 \cdot L_{eq} - 5.9537) + 0.130(0.0251 \cdot D - 0.2344) - 0.128(0.9662 \cdot IACC + 0.1566) + 0.136 \\
&= 0.0075 \cdot L_{eq} + 0.0033 \cdot D - 0.1237 \cdot IACC + 0.1055
\end{aligned} \tag{7}$$

3. Model test of the same set

Based on the values of the SSP in TABLE II and the calculations of Equation (6) and (7), a test of the same set for all 21 soundscape samples was carried out to verify the effectiveness of the two evaluation models of Section 3.4.1-2. Although the absolute value of regression coefficients are in a relatively low range (0.082~0.136 for the semantic model, and 0.1732~0.5235 for the acoustic model), as the total regression Sig. value is 0.025, these two models are of statistical significance. Thus, according to the results shown in Fig. 12, both the semantic model with a correlation coefficient of 0.6438 and the acoustic model with a correlation coefficient of 0.5361 can precisely predict the trend of the values of the SSP from the auditory experiment of Section 2.3, except for some minor differences with the exact values.

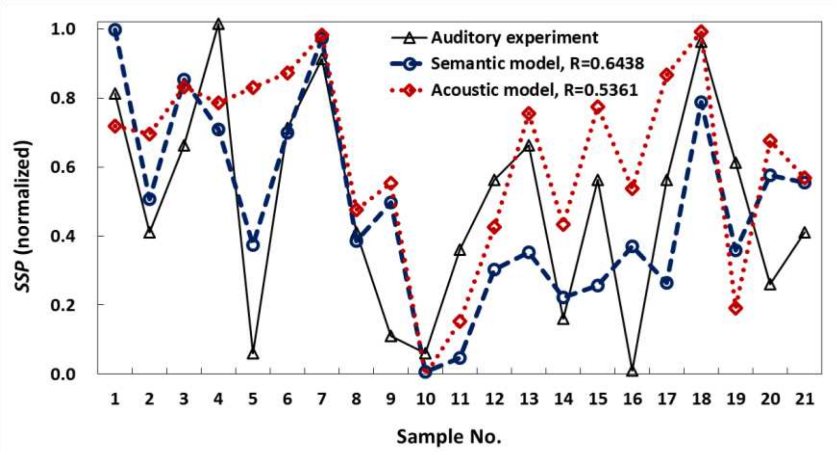


Fig. 12. The SSP values based on the auditory experiment, semantic and acoustic models

4. Conclusions

As discussed above, in current soundscape research efforts, many studies are focused on creating a link between acoustic parameters and psychoacoustic parameters, semantic parameters or human awareness itself and on providing an objective model to predict the corresponding subjective perception. Thus, starting from the analysis of the independent effect of 10 semantic parameters and two main acoustic parameters L_{eq} and IACC, the purpose of this paper was to try to reveal an evaluation model to predict the subjective spatial perception of soundscape from the above parameters.

The results of the correlation analysis and the independent effect show that the more noise (QN) an audience perceives, the less spatially aware they become, while the more closer (CF), more directional (DO), sound source image variations (SIV), numbers of sound sources (NSS) and dynamic (D) parameters the soundscape has, the better the spatial awareness would be. Then, the sensations of roughness (RS), sound intensity (WS), transient dynamic (TrD) and the values of L_{eq} and IACC have a suitable range for a better subjective spatial perception. Finally, a better spatial awareness seems to promote the preference (SPA and BL) slightly for an audience in a real soundscape environment.

In other words, according to the analysis of inter-relationships among all of the parameters, the awareness of the subjective spatial perception depends on the human sensations of sound intensity and its variations (SI mode), sound contents (SC mode) and sound directivity (SD mode). If assessments of the three sensations (the semantic components, SSP_{SI}, SSP_{SC} and SSP_{SD}) are given in simple a 5-point Likert scale, then the subjective spatial perception (SSP) of a binaural-recorded soundscape sample is easy to predict by using Equation (6), or Equation (7) can be used to calculate the values of L_{eq}, D (dynamic) and IACC with a known awareness of sound contents.

Based on the above auditory experiments, PCA and HCA analysis, this study suggests a SSP_{SI}-SSP_{SC}-SSP_{SD} semantic model and a L_{eq}-D-IACC acoustic model to predict the subjective spatial perception (SSP) of a binaural-recorded soundscape sample, however, there are still any other spatial factors of the sound fields such as W_{IACC} (width of the IACC or

IACF), τ_{IACC} (inter-aural delay time at which the IACC is observed) and ASW (apparent source width) [24] to be examined for the spatial sensations of binaural signals in the further study. But, these two models could be important for simplifying the numbers of evaluation parameters of spatial awareness and give a quantified indicator between the sound space perception and landscapes during the soundscape planning process [25, 26].

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