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JASA ARTICLE

Characterization of soundscape assessment in outdoor public spaces of urban high-rise residential communities[a)]

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ABSTRACT:

Soundscape perceptual models were developed in various contexts. However, as the outdoor public space in high-rise residential communities differs in terms of space planning and management, the soundscape perceptual characteristics are still unclear. In this study, an on-site survey was conducted to obtain the perceptual dimensions of soundscape in outdoor public spaces in urban high-rise residential communities based on evaluations of residents. Meantime, the soundscape of the space in different community layouts were compared. It was found that: (1) Four dimensions of outdoor soundscape in high-rise communities were extracted, namely *Relaxation*, *Communication*, *Quietness*, and *Spatiality*. The first three dimensions were positively correlated with overall soundscape satisfaction significantly. (2) *Relaxation* was mostly correlated with dominance of noise; *Communication* and *Quietness* were primarily related to sounds from human beings. (3) Lower traffic noise and higher levels of human sounds were perceived in enclosed communities, resulting in higher *Relaxation* and lower *Quietness* scores in outdoor public spaces in enclosed communities than non-enclosed ones. These findings evoke insights into the understanding of soundscape assessment in different contexts, and provide implications for sound environment design in urban high-rise communities. https://doi.org/10.1121/10.0022531

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I. INTRODUCTION

As urbanization proceeds worldwide, high-rise residential buildings have become one of the dominant forms of urban housing, especially in East Asia. The outdoor public spaces of high-rise residential areas play an important role in outdoor entertainment, exercise, and neighborhood social interaction, which could enhance quality of life.[1–4] The acoustic environment of outdoor spaces in residential districts is a crucial component that affects comfort. Abundant previous studies on the acoustic environment of residential areas were focused on traffic noise and objective parameters. The traffic noise level and distribution were affected by urban morphological factors, including building density, noise barriers, building height, opening size, and setback distance along the street.[5,6] In outdoor public spaces in high-rise residential estates, sound levels and reverberation times were influenced by the distance of sound source, building layout, and building scale.[7] Despite that traffic noise and characteristics of sound field are important representations of acoustic environment, these descriptions remain at an objective level and focus at the adverse effects of noise.[8–10] Soundscape approach, on the other hand, values the subjective human experience and adopts a neutral attitude, regarding the sound as a resource rather than mere pollution.[11,12]

Distinct from the concept of "annoyance" typically adopted in assessment of community noise, the characterization of soundscape is typically complex and integrated with multiple dimensions. The composition of dimensions is typically influenced by the feature of place, the type of sound sources, and the context of the user group.[13–17] A number of models of soundscape assessment have been established for various types of spaces—for instance, in urban open public spaces, urban shopping streets, and indoor livings rooms.[18–20] In addition, soundscape dimensions constructed from particular groups or regarding particular soundscapes were explored.[21,22] All these constructs varied in the structure and content as the perceived dimensions typically reflect the user's potential demand and expectation for the acoustic environment, such as *Communication* in urban open public spaces,[18] the *Playfulness* in urban shopping streets,[19] the *Peacefulness* for children,[21] and the *Representativeness* regarding soundscapes worthy of preservation.[22] In 2010, three perceptual principal components derived from evaluation of multiple types of soundscapes were extracted,[23] namely *Pleasantness*, *Eventfulness*, and *Familiarity*, which have been widely acknowledged as the perceived affective quality of soundscape, and were adopted as an universal scale in soundscape assessments.[24–27] Meantime, debate has been raised on the perceived affective quality,[28] by comparison, with the origin of the concept of "affective quality" originated from core affect theory and raised by Russell[29,30] in emotional psychology.

While existing studies on soundscapes are primarily centered in urban public spaces, in China, the outdoor public

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spaces in high-rise estates are in an apparently different context. Typically, high-rise estates in China are closed or semi-closed with railings, and the public spaces inside the estate were mainly occupied by residents living within the compound. For security reasons, most high-rise residential areas are managed by property companies with access control systems. All residents share ownership of the outdoor space and expend monthly for security, facility management, and environmental maintenance. Another distinction of this space lies in the relationships being cultivated and the sense of community among the neighbors who utilize this space on a daily basis and meet frequently.[31,32]

Particularly compared with low-rise housing, residents of high-rise districts showed more problems, such as greater psychological problems like loneliness, stress, and anxiety,[33–37] which highlight the prospect for utilization of the outdoor resources. In East-Asian areas, such as China, Singapore, and South Korea,[38,39] a number of studies have been conducted on soundscape in the outdoor public spaces in high-rise communities, such as noise distribution pattern and sound propagation,[5,7,40,41] and factors affecting soundscape quality.[25,42] However, the perceptual characteristics of this space is still not clear. In addition, high-rise settlements were built in a variety of scales and layouts, and the impact of this factor on soundscape is still unknown.

Therefore, the purpose of this study is to characterize the soundscape assessment in outdoor spaces of high-rise residential communities in high-density cities. The research questions are as follows: (1) What are the dimensions of soundscape assessment in outdoor public spaces of high-rise residential communities in high-density cities? (2) What are the acoustical factors influencing the dimension scores of soundscape? (3) What are the differences of sound sources and dimension scores between different layouts? In contrast to experimental approaches, on-site questionnaire surveys were conducted, as an exploration of these questions in real context could help establishing a deeper understanding of soundscape assessment and characteristics in the urban high-rise context.

II. METHOD

A. Pilot study

A number of previous studies were conducted in laboratories under controlled conditions[20,23] in which information, including the social/cultural background of the subjects and the expectations of the environment, could be ignored. In this study, the perceptual dimensions of the real residents living in high-rise settlements were focused; therefore, on-site survey approach was adopted.

The primary aim of the study was to obtain the dimensions of soundscape assessment. To extract the fundamental dimensions, a pilot survey was conducted before the formal investigation to obtain sufficient attributes suitable in describing residential soundscape. In the pilot survey, to help the residents establish a basic understanding, a short interview was first conducted, in which questions about their attitudes, evaluations, and expectations of soundscape were briefly inquired. Then, the respondents were asked to rate on soundscape perceived at that time on a list of 30 antonym attribute pairs with a 7-point bipolar scale. Some of these attributes were extracted from previous studies on urban soundscape and perceived affective quality,[18,19,23] and some were compiled specifically for this study, according to the narratives of residents, such as *dangerous-safe*, *unclear-clear*, and *deadly echoed*. During the interviews, it is found that descriptions of sound were strongly linked to emotional feelings, in narratives, such as "This noise is unfamiliar and made me alerted and uncomfortable," "The horn is too sharp and unharmonious to suit this place." Therefore, different from studies on a psychological perspective, which focused on attributes describing internal emotions, attribute pairs describing sound were retained. The attribute pair list was presented in Chinese, and were translated referring to the Soundscape Attributes Translation Project.[43]

The pilot study was carried out in the outdoor spaces of four high-rise residential communities. Sixty randomly selected residents were asked to rate the 30 antonym attribute pairs. Meantime, each respondent was allowed to skip the attribute pairs that he/she did not find easy to understand or interpret. Subsequently, the attribute pairs rated by less than 60% of the respondents were considered inappropriate to evaluate soundscape in Chinese high-rise communities, such as *eventful–uneventful* and *cold–warm*. Attributes rated by more than 60% of the respondents were retained in the formal investigation, including *unpleasant–pleasant*, *uncomfortable–comfortable*, *noisy–quiet*, *unfriendly–friendly*, *dangerous–safe*, *tense–relaxed*, *unfamiliar–familiar*, *unharmonious–harmonious*, *meaningless–meaningful*, *monotonous–various*, *unclear–clear*, *disordered–ordered*, *deep–high pitched*, *weak–strong*, *unstable–stable*, *natural–artificial*, *directional–everywhere*, and *echoed–deadly*.

B. Site selection

The formal investigation was conducted in Tianjin, a typical city in northern China. Tianjin is representative of its high-density feature, with a total population of 13.7×10^6 and an urbanization rate of 84.7%. The high-rise residential compounds in the city typically consisted of a number of private residences and shared stairs, elevators, and outdoor public space(s). For security reasons, most of the residential compounds are gated or semi-gated, namely, each entire compound is surrounded by walls or railings with one or several entrances with access control systems.[44] The outdoor public spaces inside the compounds are important places for the residents' daily activities, such as rest, strolling, jogging, and neighborhood interaction.

The selection of investigation sites was determined in consideration of the diversity in the size and class of the residential compounds. Distinct difference could be observed in terms of the size of the outdoor public space, the scale and layout of the high-rise communities; therefore, they were divided into two categories: enclosed residential communities and non-enclosed residential communities. It was observed that the outdoor public space in the enclosed community is typically larger than 5000 m^2, and is surrounded by more than ten high-rise buildings with clear space boundary, while the non-enclosed communities exploit the limited outdoor space adjacent to the high-rise buildings, with an area of less than 2500 m^2. *As more questionnaires could be obtained in each enclosed residential community than in each non-enclosed one, more non-enclosed communities were included in the survey to reach a quantity balance of the total questionnaires between the two types of communities.* Finally, 12 high-rise residential communities were selected, as shown in Fig. 1 and Fig. 2, including three enclosed communities and nine non-enclosed communities. The enclosed residential communities were labelled as E1–E3, including Baolongwan Garden, Tianyue Garden, and Jingde Garden. In contrast, the non-enclosed residential compounds were labelled as N1–N9, including Dayuecheng Estates, Chengnan Garden, Tongfang Garden, Yidun Rose Apartment, Bolang Garden, Xingye Garden, Kaisheng Garden, Linwei Garden, and Fenghu Li. All communities are located in the central area of Tianjin. They are adjacent to urban major roads and far from railway, airport, and industrial zones. Therefore, the primary noise interference of the surrounding environment is from urban traffic. More information about each community was given in Table I.

C. Questionnaire design

The questionnaire consisted of three parts. First, 18 antonym attribute pairs obtained in the pilot survey were illustrated using a 7-point bipolar rating scale. Second, evaluation of perceived sound sources were collected. The dominant sound sources were investigated by the following question: "To what extent do you presently hear the following four types of sounds?" The sound sources were divided into four categories: traffic noise, sounds by human, natural sounds, and other noise. A 5-point scale evaluation was used (1: Not at all; 2: A little; 3: Moderately; 4: A lot; 5: Dominates completely). Third, residents' overall satisfaction with the current soundscape was rated using a 5-point scale (1: Very good; 2: Good; 3: Neither good, nor bad; 4: Bad; 5: Very bad). At the end of the questionnaire, demographical information of respondents was collected, including age, gender, education level, and work status. This part of the questionnaire was derived from the ISO/TS 12913-2,[45] the SSID Protocol,[46] and was translated into Chinese.

D. On-site measurement and acoustic parameters

A number of studies adopted an artificial head (i.e., Neumann KU100, Berlin, Germany) or binaural instruments to capture the acoustic environment features.[47–49] In this study, a calibrated portable recorder (SQoBold, HEAD acoustics GmbH, Herzogenrath, Germany) with head-mounted microphones (BHS II, HEAD acoustics GmbH) was utilized, which was validated in a number of soundscape surveys.[50,51] The duration of the recording was set to 1 min for each questionnaire, which was sufficient in calculations of acoustical parameters.[18,52] The measurement process was compiled with ISO/TS 12913-2.[45] Respondent was silently listening to the surrounding sound environment. At the same time, the measurement was conducted. While the questionnaire was being filled out by the respondent, an operator wearing the binaural headset with a windshield was standing (or sitting with the respondent) next to the respondent at a distance of approximately 1.5 m. The sampling frequency and the bit depth of the binaural recording were 48 kHz and 24 bits, respectively.

Acoustic parameters accounting for energetic, temporal, and spectral features, were obtained from the binaural recordings. In terms of total sound energy, the sound pressure level A-weighted L_{Aeq} was selected. The difference between the 10th and 90th percentile levels (L_{A10}–L_{A90}) was used to describe the temporal variability of the sound environment. As for spectral characteristics, the difference between A- and C-weighted sound pressure levels (L_{Ceq}–L_{Aeq}) was calculated to describe relatively low-frequency content of sounds. In addition to decibel

FIG. 1. (Color online) Study sites: the 12 urban high-rise residential communities in Tianjin, China, consisted of three enclosed communities labelled with yellow (E1–E3) and nine non-enclosed communities labelled with red (N1–N9).

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FIG. 2. (Color online) Photographs of 12 high-rise communities taken with a spherical panoramic camera (Insta-360 Pro, Shenzhen, China) and transformed to human eye views.

parameters, a number of non-decibel parameters were found to be strongly relevant to soundscape evaluation;[20,21,23] therefore, psychoacoustic parameters, including loudness, roughness, sharpness, and fluctuation strength were calculated. Wind noise and sounds made by the operator or the respondent were removed from the audio clips before the calculations of acoustical parameters. All decibel parameters and psychoacoustic parameters were calculated in a modular software platform (ArtemiS SUITE 7.0, Head Acoustics GmbH) for both the left and right channels.[26,53] Following the instructions proposed in ISO/TS 12913-2,[45] a maximum value of left and right channels of the binaural recordings was adopted for the indication of loudness N_{avg}, N_{10}, and N_{10}–N_{90}. The average values of both ears were calculated for other parameters.

E. Respondents

A total of 583 valid questionnaires were collected in 12 high-rise residential communities, in which 310 were collected in E1–E3 and 273 in N1–N9. The demographical background of the subjects is given in Table II. Chi-square test showed that there were no significant differences in the gender and occupational distribution of the respondents between two groups of residents (Pearson Chi-Square test significance = 0.498 and 0.518, respectively). However, the proportion of younger respondents and highly educated people was relatively higher in the non-enclosed compounds (Pearson Chi-Square test sig. = 0.034 and 0.042, respectively) than that in enclosed communities.

F. Data analysis

In this paper, the statistical software package SPSS (IBM, Armonk, NY) was used to establish a dataset of subjective responses from questionnaires and acoustic parameters from on-site measurements. Factor analysis was adopted in the semantic differential analysis, in which soundscape perceptual dimensions and factor scores were obtained. The P–P plot showed a normal distribution of the overall dataset. Therefore, the Pearson correlation test was used to find out the relationships between soundscape dimensions and overall satisfaction, as well as the correlations between sound sources, acoustic parameters, and dimension scores. Independent samples t-test was performed to examine a significant difference between soundscape scores and perceived sound sources in enclosed and non-enclosed layouts. In all analyses, a p-value less than 0.05 was used as the criterion to determine statistically significant differences.

III. RESULTS

A. Perceptual dimensions of the soundscape

A factor analysis was performed based on all 583 questionnaires collected from the field investigation to extract the perceptual factors of soundscape. The Kaiser–Meyer–Olkin (KMO) value of the factor analysis was 0.892, and the corresponding Bartlett's spherical test result was $p = 0.000 < 0.01$, which indicated that the result could be considered as quite stable. Table III shows the result of the varimax rotated principal component analysis that was used to extract the main factors. Four main factors were identified, explaining 26.1%, 16.4%, 16.1%, and 7.5%, respectively, of the total variance in the dataset.

Factor 1 (26.1%) was mainly explained by *unfriendly–friendly*, *dangerous–safe*, *tense–relaxed*, *unpleasant–pleasant*, *unfamiliar–familiar*, *unharmonious–harmonious*, and *uncomfortable–comfortable*. As these words were

TABLE I. Information about the 12 high-rise communities.

Type	Community name	Floor area ratio	Households	Number of buildings	Compound area/m^2	Outdoor plaza area/m^2
E1	Baolongwan Garden	3.2	1636	15	39 693	10 710
E2	Tianyue Garden	2.9	1714	17	80 216	10 192
E3	Jingde Garden	3.0	1679	14	67 203	5913
N1	Dayuecheng Estates	4.4	963	5	15 580	1332
N2	Chengnan Garden	2.7	1280	9	42 120	2376
N3	Tongfang Garden	3.8	914	11	22 204	1628
N4	Yidun Rose Apartment	4.5	674	4	12 826	1755
N5	Bolang Garden	4.4	620	5	15 246	1023
N6	Xingye Garden	3.5	1038	7	20 174	1517
N7	Kaisheng Garden	3.0	960	5	18 904	693
N8	Linwei Garden	2.6	1203	6	32 963	1312
N9	Fenghu Li	4.6	1090	5	18 655	1200

mainly associated with emotional valence of pleasure and safety caused by the acoustic environment; therefore, factor 1 was labelled as *Relaxation*. Factor 2 (16.4%) was best explained by *meaningless–meaningful*, *monotonous–various*, *unclear–clear*, *disordered–ordered*, and *deep–high pitched*. These words were mostly associated with the semantic information carried by the sound and the appearance of human voices, which indicated the presence of sounds from residents engaged in neighborhood social interaction. Therefore, factor 2 was labelled as *Communication*. Factor 3 (16.1%) was generally explained by *weak–strong*, *unstable–stable*, *noisy–quiet*, and *natural–artificial*. These words were associated with the strength, stability characteristics, and type of sound environment; therefore, factor 3 was labelled as *Quietness*. Factor 4 (7.5%) was principally explained by *directional–everywhere* and *echoed–deadly*, and therefore was labelled as *Spatiality*.

The above analysis based on all subjects exhibited a four-dimension model of the soundscape in outdoor public spaces in high-rise communities. Due to the classification based on layout of the compounds, factor analysis for enclosed and non-enclosed communities were conducted separately, which exhibited moderate difference. This content was further discussed in Sec. III 3.

TABLE II. Demographical distribution of respondents.

		Enclosed communities		Non-enclosed communities	
		Female (%)	Male (%)	Female (%)	Male (%)
Aging group	<30	52.3	44.0	59.6	49.6
	30–60	23.9	23.9	28.2	23.9
	>60	23.9	32.1	12.2	26.5
Education	Middle school or lower	16.5	20.9	7.1	17.1
	University or college	34.1	26.9	35.9	38.5
	Postgraduate or higher	49.4	52.2	57.1	44.4
Occupation	Working	19.9	26.1	17.3	28.2
	Retired	33.0	23.9	39.7	24.8
	Others[a]	47.2	50.0	42.9	47.0

[a]Includes students, unemployed, confidential, and other occupational situations.

The results of Pearson's correlation coefficients between metric of dimension scores and the overall soundscape satisfaction were given in Table IV. Overall soundscape satisfaction was positively correlated with factors of *Relaxation*, *Communication*, and *Quietness*. This indicates that residents prefer a pleasant, communicative, and quiet acoustic environment. No significant correlation was found between *Spatiality* score and soundscape satisfaction. Therefore, dimension *Spatiality* was excluded in the following analysis.

B. Relationships between dimension scores, dominance of sound sources, and acoustic indicators

The correlation between dimension scores, sound sources, and acoustic indicators were examined in Table V. Traffic noise and other noise had a negative effect on the dimension scores. No correlation was found between natural sounds and dimension scores, which is different with studies suggesting natural sounds were able to induce relaxation and enjoyment.[54,55] Interestingly, effect of sounds from human beings were bidirectional, which demonstrated a positive correlation with *Relaxation* and *Communication*, but a negative correlation with perception of *Quietness*. Notably, the coefficients with acoustic and psychoacoustic indicators were generally weak compared with coefficients with sound sources, especially for *Relaxation* and *Communication*, which suggested an information loss of the indicators in identifying the dominance of sound sources.

C. Comparison of soundscape between enclosed and non-enclosed communities

The difference of perceived sound sources in enclosed and non-enclosed communities was exhibited in Fig. 3. As for traffic noise and sounds from human beings, statistically significant differences were found between enclosed and non-enclosed communities. Notably, the dominant sound source in enclosed and non-enclosed communities were sounds from human beings and traffic noise, respectively,

TABLE III. Factor analysis of the soundscape assessment: overall results of enclosed and non-enclosed communities. KMO value, 0.892; Cumulative, 66.1%; extraction method, principal component analysis; rotation method, varimax with Kaiser normalization; N = 583.

	Factors			
Attributes	1(26.1%)	2(16.4%)	3(16.1%)	4(7.5%)
Unfriendly–friendly	0.822	0.183	0.121	−0.168
Dangerous–safe	0.813	0.068	0.165	−0.231
Tense–relaxed	0.782	0.174	0.285	0.076
Unpleasant–pleasant	0.764	0.286	0.384	0.109
Unfamiliar–familiar	0.736	0.103	0.001	−0.294
Unharmonious–harmonious	0.731	0.273	0.351	0.135
Uncomfortable–comfortable	0.728	0.278	0.429	0.085
Meaningless–meaningful	0.282	0.762	0.027	0.019
Monotonous–various	0.216	0.720	−0.179	0.109
Unclear–clear	0.221	0.716	0.258	−0.239
Disordered–ordered	0.259	0.712	0.235	−0.120
Deep–high pitched	−0.054	0.693	−0.186	−0.015
Weak–strong	−0.254	0.031	−0.758	0.111
Unstable–stable	0.186	−0.020	0.737	0.105
Noisy–quiet	0.395	0.131	0.732	0.085
Natural–artificial	−0.072	0.065	−0.689	0.093
Directional–everywhere	0.051	−0.143	−0.062	0.737
Deadly–echoed	−0.221	0.058	0.055	0.688

suggesting the outdoor spaces in non-enclosed residential compounds were more fragile to traffic noise. Conversely, in the enclosed neighborhood, auditory sensation was dominated by sounds from activities of surrounding residents.

Regarding acoustical indicators illustrated in Table VI, the significant difference in L_{Ceq}–L_{Aeq} indicates an energy accumulation in the low-frequency range in non-enclosed communities and is coherent with Fig. 3 in which traffic noise was the dominant source in non-enclosed communities. Regarding indicators characterizing the dynamic feature of sound environment, the values were higher in enclosed communities, indicating the presence of non-stable sounds, such as human voices and children playing.

To examine the difference of soundscape assessment between the two types of residential communities, factor analysis was carried out based on the enclosed/non-enclosed communities separately. For data in enclosed communities, four dimensions cover 62.3% of the total variance, as shown in Table VII, where the composition of each dimension was the same as those obtained from overall subjects. For data in non-enclosed communities, three dimensions cover 65.4% of the total variance, as shown in Table VIII. For dimensions representing *Communication* and *Spatiality* in non-enclosed

TABLE IV. Pearson's correlations between dimensions of soundscape evaluation and overall soundscape satisfaction.

	Relaxation	*Communication*	*Quietness*	*Spatiality*
Correlation coefficient	0.505[a]	0.219[a]	0.436[a]	−0.040
Significance	0.000	0.000	0.000	0.336

[a]$p < 0.01$.

TABLE V. Correlation between soundscape dimension scores, sound sources, and acoustic indicators. *$p < 0.05$, **$p < 0.01$.

	Relaxation	*Communication*	*Quietness*
Traffic noise	−0.284**	−0.153**	−0.206**
Sounds from human beings	0.122**	0.374**	−0.310**
Natural sounds	0.021	0.046	0.042
Other noise	−0.289**	−0.018	−0.040
L_{Aeq}	0.037	0.159**	−0.077
L_{Ceq}–L_{Aeq}	−0.011	−0.271**	0.019
L_{A10}–L_{A90}	−0.007	0.236**	−0.168**
N_{avg}	−0.091*	0.049	−0.324**
N_{10}	−0.090*	0.086*	−0.303**
N_{10}–N_{90}	−0.082*	0.125**	−0.229**
R	−0.077	0.082*	−0.269**
FS	0.074	0.209**	−0.111**
S	−0.130**	0.017	−0.086*

communities, the composition of the two dimensions remained the same to those in enclosed communities. However, it is notable that the attributes correlated with *Quietness* and *Relaxation* in enclosed communities were mixed in non-enclosed communities, and these attributes together constituted the first dimension related to the combined feeling of relaxation and quietness.

The merging of *Relaxation* and *Quietness* in non-enclosed communities could be led by the dominance of a particular sound source, which was mentioned in a previous study.[18] Specifically, in non-enclosed high-rise communities, the dominance of traffic noise has a negative effect on both quietness and relaxation, leading to a co-linearity of the attributes associated with these dimensions, which resulted in the merging of the two dimensions. Whereas in enclosed communities, the dominance of sounds from residents led to a lower sense of quietness and a higher sense of relaxation; therefore, the two dimensions diverged.

Consistency with the above analysis was validated by examining the correlation of dimension scores extracted from the overall subjects. *Relaxation* and *Quietness* exhibited a significant positive correlation in non-enclosed communities ($r = 0.324$, $p = 0.000$). This indicates that there is a strong co-linearity between the two dimensions in non-

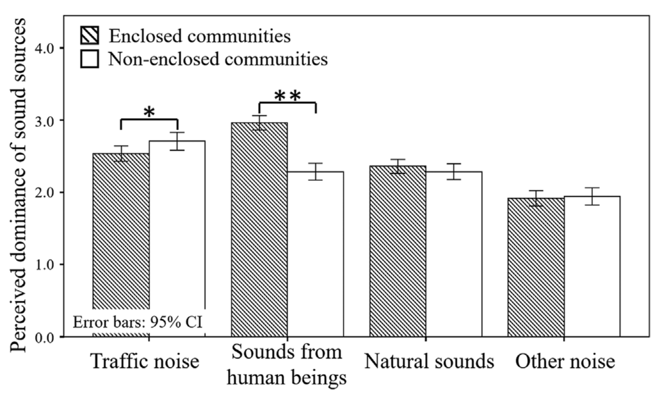

FIG. 3. Comparison of perceived dominance of sound source between enclosed and non-enclosed communities.

TABLE VI. Comparison of acoustic indicators between enclosed and non-enclosed communities.

Indicator	Type	Mean	95% Confidence interval		P-value
			Lower	Upper	
L_{Aeq}	Enclosed	57.93	57.46	58.40	0.000
	Non-enclosed	55.07	54.51	55.62	
L_{Ceq}–L_{Aeq}	Enclosed	4.85	4.51	5.18	0.000
	Non-enclosed	7.97	7.46	8.47	
L_{A10}–L_{A90}	Enclosed	7.32	6.99	7.65	0.001
	Non-enclosed	6.50	6.14	6.87	
N_{avg}	Enclosed	9.63	9.41	9.86	0.000
	Non-enclosed	8.77	8.41	9.14	
N_{10}	Enclosed	12.09	11.75	12.42	0.000
	Non-enclosed	10.93	10.42	11.43	
N_{10}-N_{90}	Enclosed	4.41	4.18	4.65	0.004
	Non-enclosed	3.86	3.56	4.16	
R	Enclosed	1.61	1.58	1.63	0.000
	Non-enclosed	1.51	1.47	1.54	
FS	Enclosed	0.023	0.021	0.025	0.000
	Non-enclosed	0.017	0.014	0.020	
S	Enclosed	1.64	1.61	1.66	0.122
	Non-enclosed	1.68	1.63	1.72	

TABLE VII. Factor analysis of the soundscape assessment: results of enclosed communities. KMO value, 0.848; cumulative, 62.3%; extraction method, principal component analysis; rotation method, varimax with Kaiser normalization; N = 310.

Attributes	Factors			
	1(26.1%)	2(16.1%)	3(11.5%)	4(8.6%)
Unpleasant–pleasant	0.816	0.254	0.269	0.141
Tense–relaxed	0.813	0.125	0.128	0.043
Unfriendly–friendly	0.804	0.112	−0.041	−0.236
Dangerous–safe	0.790	0.008	−0.003	−0.315
Unharmonious–harmonious	0.774	0.275	0.175	0.135
Uncomfortable–comfortable	0.773	0.218	0.340	0.116
Unfamiliar–familiar	0.654	0.037	−0.208	−0.392
Meaningless–meaningful	0.171	0.802	−0.130	−0.046
Deep–high pitched	−0.054	0.735	−0.213	0.083
Monotonous–various	0.173	0.702	−0.227	0.060
Unclear–clear	0.252	0.702	0.219	−0.329
Disordered–ordered	0.281	0.689	0.212	−0.225
Weak–strong	−0.193	0.114	−0.687	0.208
Noisy–quiet	0.457	0.028	0.665	0.150
Unstable–stable	0.023	−0.063	0.659	0.242
Natural–artificial	0.021	0.057	−0.470	0.063
Deadly–echoed	−0.159	0.015	0.062	0.677
Directional–everywhere	0.085	−0.145	−0.060	0.651

enclosed communities where traffic noise dominated, which is likely to be the reason for the integration of relaxation and quietness. On the contrary, a significant negative correlation ($r = -0.219$, $p = 0.000$) was observed in the enclosed high-rise communities, although the coefficient was lower compared with that in non-enclosed communities. This is noteworthy in that "relaxing" and "noisiness" were treated separately when sounds from humans were dominant, and suggests that appropriate loudness from the activities of the community residents could result in a higher sense of *Relaxation*.

Except that the attributes related to quietness and relaxation in the non-enclosed communities were merged into one dimension, the other dimensions (*Communication* and *Spatiality*) between two types of communities were completely congruent. In addition, three replicated tests of exploratory factor analysis were performed, and each test employed a random subset (50%) of the overall dataset.[23] The same four dimensions were obtained except for minor differences in the order and loadings of the attributes, which suggested the four-dimension construct to be quiet stable. Therefore, it is suggested that the soundscape construct in non-enclosed communities could be regarded as a special case, which was simplified as relaxation and quietness, are highly positively correlated under traffic noise–dominated scenarios. In addition, the soundscape construct from overall dataset was a generalized model applicable to both types of outdoor spaces of urban high-rise communities.

Owing to the universality of the perception model from overall subjects, dimension scores were calculated and based on this model and an independent samples t-test was adopted to examine the differences in the dimension scores, as illustrated in Fig. 4. In enclosed communities, the scores of *Relaxation* and *Communication* were significantly higher than in non-enclosed communities ($p = 0.000$ and $p = 0.000$, respectively), while *Quietness* was significantly lower than in non-enclosed communities ($p = 0.000$).

This unveiled the effect of building layout on community soundscape: it was quieter but less relaxing and social in non-enclosed communities than in enclosed communities. It is also important to note that this does not mean the soundscape in enclosed communities were more satisfying than in non-enclosed communities, as the overall soundscape satisfaction is influenced by the combination of three dimensions. Independent samples t-test showed no statistically significant differences between the two types of communities in overall soundscape satisfaction ($p = 0.916$), suggesting that the residents presumably assessed the two soundscape traits with equal satisfaction.

Combining Figs. 3 and 4 and Table VI, it was suggested that the significant difference of dimensions scores could be attributed to the difference of sound source composition in enclosed and non-enclosed communities, respectively. Compared with non-enclosed communities, enclosed ones were more effective in isolating traffic noise and promoting communal activities, which led to a rise in sounds from the residents. Specifically, while the L_A and loudness in enclosed communities were significantly higher than that in non-enclosed communities shown in Table VI, the *Relaxation* in enclosed communities was higher. This implied the inapplicability of existing level-based and psychoacoustic indicators in describing the acoustic environment to represent the authentic evaluation of residents in non-laboratory scenes.

TABLE VIII. Factor analysis of the soundscape assessment: overall results of enclosed and non-enclosed communities. KMO value, 0.916; cumulative, 65.4%; extraction method, principal component analysis; rotation method, varimax with Kaiser normalization; N = 273.

	Factors		
	1(42.5%)	2(15.1%)	3(7.8%)
Uncomfortable–comfortable	0.871	0.277	−0.078
Unpleasant–pleasant	0.864	0.277	−0.074
Unharmonious–harmonious	0.845	0.217	0.020
Tense–relaxed	0.824	0.202	−0.058
Noisy–quiet	0.821	0.227	0.023
Weak–strong	−0.818	−0.010	−0.028
Natural–artificial	−0.817	−0.081	0.025
Unstable–stable	0.809	−0.022	0.093
Dangerous–safe	0.755	0.192	−0.302
Unfriendly–friendly	0.753	0.238	−0.259
Unfamiliar–familiar	0.645	0.165	−0.328
Monotonous–various	0.100	0.737	0.141
Meaningless–meaningful	0.391	0.685	0.091
Disordered–ordered	0.408	0.652	0.017
Deep–high pitched	−0.174	0.645	−0.232
Unclear–clear	0.383	0.627	−0.096
Directional–everywhere	0.010	−0.151	0.771
Deadly–echoed	−0.152	0.176	0.657

IV. DISCUSSION

In this study, soundscape perceptual dimensions in the outdoor public spaces in urban high-rise residential communities were developed based on residents' auditory experiences, and the characteristics and causes of the dimension scores in two typical layouts of high-rise communities were further investigated. As a result, four dimensions labelled *Relaxation*, *Communication*, *Quietness*, and *Spatiality* were extracted, explaining 66.1% of the total variance. Among these, *Relaxation*, *Communication*, and *Quietness* contributed significantly to the overall soundscape satisfaction, in which *Relaxation* contributed the most. As for effects of acoustic characteristics on dimension scores, *Relaxation* was mostly affected by presence of traffic noise, while *Communication* and *Quietness* were primarily associated with perceived level of sounds from human beings.

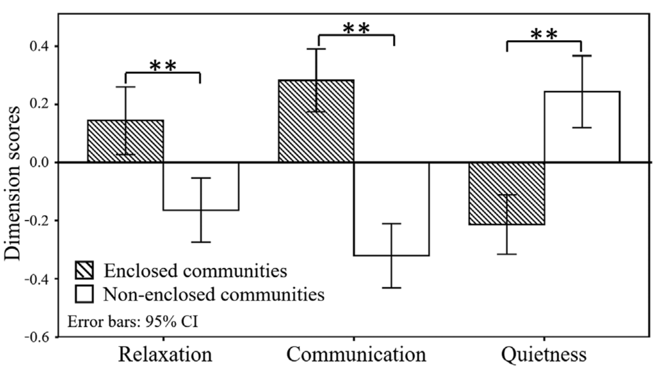

FIG. 4. Comparison of the dimension scores between enclosed and non-enclosed sites.

Moreover, the soundscape was more relaxed, communicative, and less quiet in enclosed communities compared with that in non-enclosed communities. This is because human sounds dominated in the enclosed communities, while traffic noise dominated in the non-enclosed communities.

A. Comparison of soundscape dimensions in urban high-rise residential communities and existing models

Compared to established soundscape dimensions in other studies, the dimensions of residents living in high-rise residential communities differ in structure and content. Most of the established soundscape dimensions follow a consistent pattern of orthogonal dimensions,[20,23,45] namely, the pleasantness–eventfulness model.[23,24,56] This structure is derived from the "core affect theory," which originally identified "*pleasure*" and "*arousal*" as the two core axes reflecting the construct of emotion.[29,30,57] However, in this study, while the first dimension (*Relaxation*) was extracted as a fundamental character combined with pleasantness and familiarity (and quietness for non-enclosed communities), the other dimensions (*Communication*, *Quietness*, and *Spatiality*) corresponded to the cognitive description of the sonic environment. In addition, the last dimension (*Spatiality*) has no counterpart in the affective quality model or the pleasantness–eventfulness model, and it seems that this dimension could be typically identified through on-site surveys, rather than laboratory settings.[18,58]

Similar to most studies,[18,19] the sense of *Relaxation* is the fundamental dimension of outdoor public spaces in high-rise communities, combining the emotion of pleasure with the perception of soundscape. It is worth noting that in high-rise communities, the descriptors of residents' emotions (i.e., *unpleasant–pleasant*, *uncomfortable–comfortable*) were integrated together with cognitive judgments of the sound content (i.e., *unfamiliar–familiar*). Specifically, for non-enclosed communities, sensations on the strength of the sonic environment were also included in this combination. This suggests that the residents' sense of relaxation not only is based on the direct reception of auditory stimuli, but also includes the comparison and matching of the sound with their anticipation. This composition of relaxation dimension is apparently distinct from studies in which *Familiarity* was extracted as a third principal component of soundscape.[20,21,23] Different from these studies conducted in laboratory settings, in realistic context of high-rise communities, one may become confused or even wary at unfamiliar sounds. The consciousness of familiarity may be originated from the desire for safety,[59] as this was observed in the narrations by residents in the pre-survey interviews:

> *"I will be alert when I hear some unusual sounds, because I just live here and play with my baby here every day."*

> *"I love being here every day and chatting with my familiar neighbors. Sometimes there were strangers*

I've never seen before, who made noise in the neighborhood and I was unpleasant because this is a gated community."

"I am very uncomfortable with the roar of some refitted vehicles, because it sounds very dangerous and feels like it is going to explode at any moment."

As unusual sounds might be the omen of unexpected accidents, conflicts, or anti-social behaviors, residents' emotional demand for safety needs to be satisfied by the identification of sound sources and appropriateness of the sound that match their expectations.[42,56,60,61] Another reason may be attributed to the distinct ownership and management mode of communities in China. The property ownership of the outdoor square, which could be regarded as semi-public–semi-private space inside the railings, belongs to the internal residents,[44,62] and each household pays fees monthly for the maintenance and security of the community. Therefore, residents in high-rise settlements may have less tolerance to unfamiliar sounds when embedded in the actual context, compared with findings in virtual scenes.[20,21,23] As the outdoor public space in residential communities not only is the place for daily leisure and neighborhood interaction, but also serves as the gateway to their private homes, it is presumable that the residents tend to prefer a safe, risk-free environment.

As for *Communication*, attributes included both the perception of auditory stimuli (i.e., *disordered–ordered*) and the semantic interpretation of sounds (i.e., *meaningless–meaningful*, *unclear–clear*), which is similar to findings in urban open public spaces.[18] *Communication* dimension indicates the listener's awareness of the ongoing activities in the neighborhood, especially the surrounding social interactions. This is similar to the concept of arousal proposed in the circumplex model of affect[29] and to the *eventfulness/content* in existing soundscape models.[20,23] However, in outdoor public spaces in communities, residents are mostly concerned with sounds carrying semantic information (such as meaningful) and sound events related to the holistic social atmosphere (such as *clear* and *ordered*).

Regarding *Quietness*, as a descriptive dimension, words such as weak, quiet, and stable were loaded on its positive side. As positively correlated with overall soundscape satisfaction, it seems that residents prefer controllability of the sonic environment. Similar to urban public spaces, which could also be regarded as outdoor public spaces in multi-story residential districts,[18] *Quietness* and *Relaxation* exhibited high co-linearity in non-enclosed communities where traffic noise dominated. However, the examination of the perceptual characteristics in enclosed communities revealed that relaxation and quietness were significantly diverged into two dimensions under various sonic scenarios, which could be the result of the higher resistance to urban traffic noise in enclosed communities compared with that in non-enclosed communities and in low-rise residential areas.[40] This implies that residents tend to treat relaxation and quietness separately, and suggests that soundscape evaluation in communities could be more complicated, as a quiet environment does not necessarily lead to a relaxing experience, and a noisy environment can also be very relaxing.

Particularly, it is noted from Fig. 4 that, residents seems to be more tolerant and even supportive to human sounds in their shared spaces, as lower scores in quietness resulted in higher relaxation in enclosed communities. This also challenges the adoption of sound level parameters to be indicators for the evaluation of outdoor public spaces in communities, and suggests that the content of the sound embedded in the context should be paid more attention.

The revealing of the *Spatiality* dimension indicates that residents are aware of the spatial phenomenon of sound waves reflecting back and forth between high-rise surfaces. It seems that the *Spatiality* dimension could be identified from on-site surveys,[18] rather than in laboratory sessions,[21,23] which may be due to limitation of immersive effect exhibited by soundscape reproduction process.

In summary, the construct of soundscape assessment in the outdoor spaces of high-rise communities could be seen as an enrichment of the *pleasing-arousing* circumplex model.[29,57] In contrast to Russell's model, in which attributes were introverted with the focus on the entity's emotions, plenty of soundscape attributes obtained from residents were extroverted, that is, describing the environment from a perceptual/cognitive level. This is similar to semantic differential studies in which "affective response" and "variables that produce the affective response" were both included.[28,57,63] In other words, the residents in the high-rise communities perceive and evaluate soundscape from not only the direct feelings of sound stimuli, but also the unconscious integration of cognitive judgments embedding in the sound. Nonetheless, the soundscape dimensions in the outdoor spaces in high-rise communities do not contradict Russell's model of affective quality and the existing *pleasantness–eventfulness* model can be regarded as a hierarchical layer that is extended and concretized when embedded in real context.

B. Influence of acoustical factors and demographical background on dimension scores

In previous studies, notable correlation (>0.6) was suggested between a number of acoustic parameters, e.g., L_{Aeq}, N_{10}, L_{A50},[20,21,23] and the first dimension that characterizes the emotional valence. However, in the present study, only weak correlation (<0.2) between *Relaxation* and level-based or psychoacoustic indicators were found. This is perhaps because compared with laboratory experiments, the on-site questionnaire survey was influenced by more factors, such as the background of the subjects[64,65] and visual conditions.[25,42]

It is worth noting that except for *Quietness*, the other two dimensions, *Relaxation* and *Communication*, seem to be more related to the types of sound sources. This is consistent with the findings from the dimension extraction stage, in which the meaning and the information the sound carries may be more critical compared with the immediate sensations, such as temporal/spectral features and overall level. Although correlations between sound sources and acoustic parameters were found, it seems difficult to predict the type of sound source by relying on existing acoustic or psychoacoustic indicators. Therefore, for objective evaluation and monitoring of soundscapes in outdoor public spaces in high-rise communities, it is advisable that new indicators that could characterize the type of composition of sound sources be developed. It is especially important that the new indicators could be able to simulate the process of human's extraction of sound sources and corresponding perceived dominant levels, out of the holistic sonic environment.

Whereas differences between respondents from enclosed and non-enclosed communities were found in terms of age and educational background, as illustrated in Table II, Kruskal–Wallis one-way analyses of variance were conducted to examine the difference between dimensions scores among respondents from different groups. Significant differences in relaxation scores were found between respondents of 30∼60 and respondents older than 60, with the older group evaluating higher than the middle-aged group ($p = 0.04$). No significant differences across three dimensions were found among respondents with different educational backgrounds.

To check the origin of the differences in ratings of *Relaxation* among different age groups, an analysis of covariance was conducted on the factors influencing *Relaxation*. It was found that the difference in *Relaxation* was not from age ($F = 1.035$, $p = 0.350$), but rather from perception of traffic noise, sounds from human beings, and other noise ($F = 31.769$, $p = 0.000$; $F = 14.411$, $p = 0.000$ and $F = 32.542$, $p = 0.000$, respectively). This demonstrated that the difference of dimension scores between enclosed and non-enclosed communities were led by acoustic characteristics rather than different age groups.

C. Comparison of soundscape between enclosed and non-enclosed communities: From perception to evaluation

This paper again demonstrated that the perceptual dimensions could be moderately influenced by the dominant sound type.[18] The derivation of soundscape dimensions based on homogeneous audio samples could lead to an inaccurate perceptual model, and therefore, it is advisable that studies on soundscape perceptual dimensions accommodate as many different sonic environments as possible. Consequently, the four-dimension model obtained in this study originated from the overall respondents is universal for various high-rise communities, and the integrating of *Relaxation* and *Quietness* in non-enclosed communities is embodied in the positive relationship between the dimension scores.

Although indicators L_A and N representing sound level/loudness were higher in enclosed communities than that in non-enclosed ones, the former was evaluated to be more relaxing. In contrast, the stronger energy in low-frequency range, indicated by L_{Ceq}–L_{Aeq}, may be associated with the reduction of *Relaxation*. This is clearer when examining the associations between *Relaxation* scores and perceived sound source, as the dominance of traffic noise, which was the case in non-enclosed communities, would result in more strength in the low-frequency range.

As high-rise buildings adjacent to the outdoor space could act as sound barriers, enclosed compounds performed better in resisting the invasion of traffic noise compared with non-enclosed compounds. This is similar to previous findings illustrating the influence of city morphology on traffic noise.[40,41] It is also interesting to note that the sounds from people are also related to the layout of the compound. In enclosed communities, sounds from human beings overrode traffic noise as the dominant sound source. This means that outdoor public spaces that are larger and with greater extent of enclosing are more attractive to residents, leading to more communal activities and more man-made sounds. Owing to the difference in dominant sound sources, outdoor spaces in enclosed communities have apparently different soundscape traits compared with non-enclosed communities. Therefore, strategies concerning sound environment should be taken into consideration at the beginning of the design stage.

As residents prefer relaxing, communicative soundscapes under control and hold a negative attitude toward unfamiliar and uncontrollable soundscapes, a familiar, communicative soundscape with just-right sources and loudness might be ideal. In addition, apart from the restrain of traffic noise, soundscapes from the neighborhood, which represent communal interactions and activities, should be properly encouraged.

D. Limitations

The limitation of this study mainly involved the type of neighborhoods. The results obtained in this study could be applied to urban high-rise communities with similar size, layout, and management mode, which covers most of the existing communities in China. However, it should be noted that for certain communities exceeding this range, for example, a number of upscale gated communities in which the outdoor garden is extraordinarily large, the findings of this paper may not be applicable.

V. CONCLUSION

A survey was conducted to characterize the soundscape assessment of outdoor public spaces in urban high-rise residential communities. The conclusions are as follows:

(1) Four perceptual dimensions of outdoor public space in high-rise communities were extracted, namely, *Relaxation*, *Communication*, *Quietness*, and *Spatiality*. *Relaxation* is a fundamental dimension that combines pleasantness and familiarity. *Communication*, *Quietness*, and *Spatiality* are description factors concerning the information and appearance of the sound environment. *Relaxation*, *Communication*, and *Quietness* contributed

significantly to the overall soundscape satisfaction, as improvement of these three factors led to higher chance of a positive overall evaluation. This implies resident's preference toward relaxing, communicative soundscapes under control.

(2) *Relaxation* was mostly correlated with dominance of noise, *Communication* and *Quietness* were primarily related to sounds from human beings. Compared to acoustic indicators, the evaluation of soundscape dimensions was generally more associated with perceived level of sound sources.

(3) Distinct from non-enclosed communities where traffic noise dominated, in enclosed communities, sounds from human beings dominated, leading to higher scores in relaxation and *Communication*, and a lower score in *Quietness*.

This study had several implications. First, it helps in the understanding of perceptual structure of soundscape embedded in high-rise context, as the dimensions were proposed as a concrete form of existing models.[23,57] Second, as level-based parameters failed in predicting *Relaxation* in outdoor public spaces in high-rise communities, it is advisable to develop new indicators that are able to reflect sound source composition. Monitoring of soundscape in communities differs from noise monitoring, and new guidelines are required. Third, the importance of sounds from the neighborhood members as a facilitation of *Relaxation* and *Communication* was suggested. Therefore, soundscapes from the neighborhood, which represent communal interactions and activities, should be encouraged.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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