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EFFECTS OF SOUND INTERACTION AND VISUAL STIMULI ON SOUNDSCAPE QUALITY EVALUATION

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This paper explores how significantly sound interaction and visual stimuli can influence soundscape quality evaluation in terms of four soundscape characteristics, i.e. perceived loudness, naturalness, annoyance and pleasantness. The common urban sound sources are investigated, including car traffic, bird chirping, fountains and flyover aircraft. Psychological experiment in lab and interview are employed in the study. The experiment settings are based on real soundscape recording. The quantitative experiments results show the quality of noise environments can be significantly improved by the addition of natural sounds, and demonstrate the important role of visual stimuli in quality evaluation of water sounds. The interview response shows the qualitative evidences for the soundscape quality evaluation.
Keywords: soundscape, psychological experiment, interview, noise, natural sounds

1. Introduction

With the emerging of the concept on soundscape, which is defined and explained as "Acoustic environment as perceived or experienced and/or understood by people, in context" by ISO/TC 43/SC, the research interests on urban sound environment have been extended from traditional noise control to multi-disciplinary research, including perceptual assessment, identification and taxonomy of sound events, modelling and mapping, and urban design on soundscape [1,2,3,4,5]. Improvement of soundscape quality requires study of sounds in the context of real-life soundscape, with an emphasis on human perception and experience, e.g. auditory masking, multisensory experience and interpretation of sound sources [6,7,8].

Diverse sound sources exist in urban open space, resulting in complex and unique sound environments where human act as positive perceivers. The multiple sounds interact and compete in the global sound environment, where auditory masking happens as a very significant daily-life phenomenon [9]. The traditional studies on masking effects was mainly conducted on pure tones and noises without meaning, in terms of energetic masking [9,10,11], but the research on sound source perception shows that masking effects have high relevance with sound source perception and cognition [12], hence the results within the scope of acoustics and psychoacoustics cannot not be directly borrowed by soundscape studies. Moreover, people have sound preferences related to sound sources. It has been demonstrated that in general, natural sounds (e.g. birdsong and water sounds) are wanted and top ranking in sound preference [4,13], and certain mechanical sounds (e.g. traffic and construction) are unwanted and unpleasant [14,15]. Therefore, it is crucial to study various urban sounds from certain urban sound sources with meaning, involving human perception and evaluation from the perspective of soundscape quality.

Due to the crucial role of visual-aural interaction of human perception on soundscape assessment, the integrated studies on soundscape and landscape attract more and more attention [7,16]. For instance, Pheasant et al proposed to evaluate perceived tranquillity of a location by linear expressions composed by L_{Amax}, L_{Aeq} and the percentage of presented view of natural features [16]. The landscape features, such as green area and water features, with both natural sounds and scene, have been believed to be rich in the characteristics necessary for restorative experience by reducing fatigue of directed attention [17], which is related to "informational masking".

Therefore, this study aims to explain and explore the effects of sound interaction and visual stimuli on soundscape quality evaluation with consideration of sound meaning and other contexts of soundscape. Birdsong has been also demonstrated as the most preferred natural sound in the traffic noise environment [6,7], hence two rather common urban sounds, car traffic noise and flyover aircraft noise, which have a considerable distribution in urbanised areas, were selected to study their interaction with birdsong. Vegetation and water features, which have been more often investigated as important natural landscape features and sound sources [18,19], were selected to explore the aural-visual interaction in soundscape.

2. Methodology

Based on the analysis of recordings of typical real-life soundscapes dominated by car traffic noise and birdsong, flyover aircraft noise and birdsong, car traffic noise, and water sounds, respectively, listening experiments were designed using a series of reproduced acoustic stimuli. The former two are for the effects of sound interaction, and the latter two are for the effects of visual stimuli.

2.1 Sound recordings

To reproduce acoustic stimuli and investigate the characteristics of the urban car traffic noise and birdsong environment, single-channel sound recordings were collected at a distance of 2 m from a typical main road in urban areas, namely Hoofdlaan (2×1 lane, 50 km/h), Assen, Netherlands, which lead to the city centres, with forests flanking the roads. An Edirol R-44 Portable Recorder and Tascam DR-680 digital recorder were used. The microphone height was 1.6 m. The sound samples were recorded and stored as 16-bit, 44.1-kHz wave files. The sound recordings were during sunny and windless weekdays in September. The recordings started at sunrise (approx. 07.30) and ended at sunset (approx. 19.30), considering the effect of daytime on bird chirping behaviour. Six five-minute sound recordings collected each hour over the 12 h of daytime were ultimately collected.

To reproduce acoustic stimuli and investigate the characteristics of the flyover aircraft noise and birdsong environment, single-channel sound recordings were also collected in the forest embedded in the outskirt to the southwest of Assen, where other urban sounds can be hardly heard, during sunny and windless summer mornings. The height of microphones is 1.6m. The sound samples were recorded and stored as 16bit, 44.1 kHz wave files.

The urban car traffic noise recordings were collected along a typical main road called Crookes Valley Road (2×1 lane, 50 km/h), Sheffield, UK, with trees and hedges flanking the roads. To record the spatial road traffic noise distribution, simultaneous multi-channel recordings were collected at distances of 1, 4, 9, 19, and 50 m from the side of Crookes Valley Road during summer rush hours. Furthermore, photographs were captured from the locations where the microphones were installed, facing the road, to record the scenes where the greenery is visible.

Considering the diversity of waterscape in terms of acoustic characteristics in Sheffield, a range of water sounds along the Gold Route were recorded at a distance of 1 m from the water features, including the big fountain in the Sheaf Square, the big fountain in Peace Gardens, Bakers Pool, Howard Street and the Steel Barrier in Sheaf Square. The pictures of the water features were also taken as the visual data. The height of microphones is 1.6 m.

To obtain the representative sound pressure levels and occurrence frequencies for acoustic stimulus reproduction, an analysis was carried out with 36 5-min sound recordings of traffic noise and birdsong (three recordings for every 12 h). Traffic noise and birdsong were both measured as A-weighted sound pressure level (LAeq). The analysis results show that for cars passing, the ranges of 60–70 dBA (15.9%) and 40–50 dBA (30.7%) represented the high and low sound level ranges, respectively. The variant occurrence frequencies of audible birds chirping between 07:30 and 14:30 was the factor examined in the ensuing experiment.

The recorded spectra and loudness of aircraft noise were rather various, with a range of LAeq from 44.2 to 63.3 dBA. The sound levels of the most recorded aircraft noise generally decreased after about 800Hz. Compared with the propeller noise, energy of the jet noise was more evenly distributed in frequency. Therefore, the jet noise, which is more difficult to be masked by "energetic masking", was selected, and loudness of aircraft noise was decided as the factor examined in the experiments.

2.2 Acoustic Stimuli

The acoustic stimuli were constructed based on the recorded audio using Adobe Audition CS6. The length of the acoustic stimuli was confirmed to be 30 s according to the study on the time scales of participants' constant assessments conducted by Pheasant et al [16]. The audio clips of birds chirping were cut from the single-channel sound recordings. The frequencies of birds chirping mainly fell within the range 2–10 kHz. The audio clips of cars passing, aircraft flying-over and water sounds were cut directly from the recordings captured.

Group A, in which ten acoustic stimuli were included, was formed to elucidate the influence of the sound interaction between car traffic noise and birdsong influence soundscape quality evaluation in terms of occurrence frequency of birds chirping. Five audio clips of different occurrence frequencies of birds chirping, namely, 2, 3, 4, 5, and 6 times (audible for 2 s each time), were combined with two audio clips of cars passing at 62.5 (high) and 47.5 dBA (low). Group B is composed of three acoustic stimuli to explore how the loudness of aircraft noise influence the soundscape quality evaluation. An audio clip of birds chirping (8 s, 4 events) at 52.5 dBA were combined with two audio clips of aircraft flying-over (44.2 dBA and 63.3 dBA). In Group C, the five acoustic stimuli, which were the original recordings gathered at distances of 1, 4, 9, 19, and 50m from Crookes Valley Road, were played back with and without the pictures of greenery captured at the sound recording locations. The five stimuli remained the different loudness and spectral. Group D, in which the five acoustic stimuli were presented with and without the pictures of those water features. The overall water sound levels were 59.9 dBA of the big fountain in the Sheaf Square, 63.9 dBA in the Peace Gardens, 57.9 dBA in the Bakers Pool, 49.0 dBA in the Howard Street and 54.5 dBA of the Sheaf Barrier.

2.3 Listening experiment

The listening experiment was carried out in an anechoic chamber, where the background noise level was approximately 25.0 dBA. Thirty subjects participated in the experiment, including 12 women and 18 men, aged 18-35 years. The number of participants was initially determined based on previous related studies [16] and further examined by statistical analysis. The hearing threshold levels of all participants were tested using an audiometer to ensure the normal hearing for all frequencies (125, 250, 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz). The acoustic stimuli were presented through headphones (Sennheiser HD 558) and the pictures were shown by a projector (Hitachi ED–X33), respectively. The participants were seated in a chair comfortably. Calibration was conducted by using a dummy head (Neumann KU100) before the experiment.

The participants were required to score the sounds in terms of four adjectives describing the soundscape quality, including "Loud", "Natural", "Annoying" and "Pleasant", on a scale of 0–10, with 0 representing "not at all" and 10 "extremely". The adjectives have been identified as the characteristics of soundscape quality in previous studies. Pleasantness [1,6] and annoyance [1,15] are two most commonly used characteristics, so that they were included in this study. Considering the significant roles of perceived loudness in the masking study [6] and naturalness in human relaxation [17], those two characteristics were also included.

2.4 Interview

An interview was carried out after the listening experiment for each participant. The aims of the interview were to obtain the narrative evaluation of the soundscape quality, to find out the evidences for the quantitative results of the listening experiment and to improve the experiment settings. The interview questions are: Q1: *How do the sounds feel?* Q2: *What sound do you think is particular pleasant for you?* Q3: *What sound do you think is particular unpleasant for you?* Q4*: How much do you think the sounds you listened to are different from daily-life ones?*

2.5 Data analysis

Normalisation of the responses was conducted according to Eq. (1) prior to the data analysis, as per the previous study [16], to reduce the effects of the differences in the ranges of the scores used by the participants in the evaluation.

$$X_{norm,s,q,p} = X_{s,q,p}\sqrt{\frac{\overline{\sum_{s,q} X_{s,q}^2}}{\sum_{s,q} X_{s,q,p}^2}} \quad (1)$$

where s = stimuli, q = questions, $X_{s,q,p}$ = initial answer of the person p for the stimulus s and the question q, $X_{norm,s,q,p}$ = normalized answer of the person p for the stimulus s and the question q, $\sum_{s,q} X_{s,q,p}^2$ = sum of squares of all the answers for person p, $\overline{\sum_{s,q} X_{s,q}^2}$ = average of the sum of squares for all subjects, and $\overline{\sum_{s,q} X_{s,q}^2} = \sum_{p=1}^{n}(1/p)\sum_{s,q} X_{s,q,p}^2$.

To test the agreement of the participants on the evaluation of soundscape, analysis of two-way mixed intra-class correlation (ICC) with 95% confidence interval is employed. The average intra-class correlation coefficients of Perceived Loudness, Naturalness, Annoyance and Pleasantness are 0.969, 0.946, 0.962 and 0.872, which indicates the high agreement in the judgements of the four characteristics. A one-way analysis of variance (ANOVA) was conducted to examine the statistically significant mean differences among the acoustic stimuli caused by the factors in terms of the scores of the four characteristics.

3. Results

3.1 Effects of sound interaction

Table 1 illustrates all the mean scores of the psychological evaluation of the four soundscape characteristics in Group A and B, which indicates that evaluation of soundscape quality of the car traffic noise and flyover aircraft noise was significantly influenced by the sound interaction.

Table 1: Mean values of the psychological evaluations of the four soundscape characteristics of car traffic noise and flyover aircraft noise with birdsong.

		Perceived Loudness		Naturalness		Annoyance		Pleasantness	
	Traffic noise SPLs	47.5dBA	62.5dBA	47.5dBA	62.5dBA	47.5dBA	62.5dBA	47.5dBA	62.5dBA
Occurrence frequencies of birdsong (Group A)	2	2.7	5.3	4.7	3.0	2.3	5.4	2.7	1.5
	3	2.7	5.1	5.1	3.1	2.0	5.0	4.9	1.5
	4	2.6	5.2	5.8	3.2	2.1	4.8	5.1	1.6
	5	2.7	5.1	6.2	3.4	1.7	4.6	5.5	2.2
	6	2.8	5.2	6.4	3.8	1.3	4.2	6.7	2.4
aircraft noise SPLs (Group B)	Add birdsong?	No	Yes	No	Yes	No	Yes	No	Yes
	44.2 dBA	3.1	3.3	2.4	5.5	1.7	1.8	2.1	3.7
	63.3 dBA	6.0	4.7	2.0	3.0	5.2	4.0	1.5	1.6

3.1.1 Car traffic noise and birdsong

Table 1 Group A shows the mean psychological evaluation scores of the four soundscape characteristics of the car traffic noise environments with different occurrence frequencies of birdsong, including relatively quiet traffic noise environment (i.e., 47.5 dBA) and noisy traffic noise environment (i.e., 62.5 dBA). Table 1 shows that, generally, compared with the quiet traffic noise environment, the occurrence frequencies of birdsong appear to have a weaker influence in the noisy traffic noise environments.

To study the effects of occurrence frequencies on the soundscape quality evaluation when the noise is relatively quiet, five acoustic stimuli of 42.5 dBA birdsong (2, 3, 4, 5 and 6 repetitions) combined with 47.5 dBA traffic noise in Group C were examined. The one-way ANOVA shows significant differences among the five acoustic stimuli in Naturalness, Annoyance and Pleasantness, but not for Perceived Loudness. Table 1 Group B demonstrates that when the occurrence frequency increases from 2 to 6 repetitions, Naturalness increases steadily from 4.7 to 6.4, Annoyance decreases slightly from 2.3 to 1.3, and Pleasantness increases significantly from 2.7 to 6.7. Compared with the Naturalness and Annoyance, the occurrence frequency of birdsong has a greater effect on Pleasantness.

Five acoustic stimuli of birdsong (2, 3, 4, 5 and 6 repetitions) combined with noisy traffic noise at 62.5 dBA were also examined. The one-way ANOVA only shows the significant mean differences among the five acoustic stimuli in Pleasantness, but the differences between the occurrence frequencies are small. Therefore, when the traffic noise is noisy, the occurrence frequency of birdsong has little effect on the soundscape quality. Figure 1(a) further illustrates the statistical distribution of the evaluation scores of Pleasantness with birdsong in both quiet and noisy traffic noise environments, showing a significant and highly-concordant increase of scores of Pleasantness as the sound level of traffic noise decreases from 62.5 to 47.5 dBA.

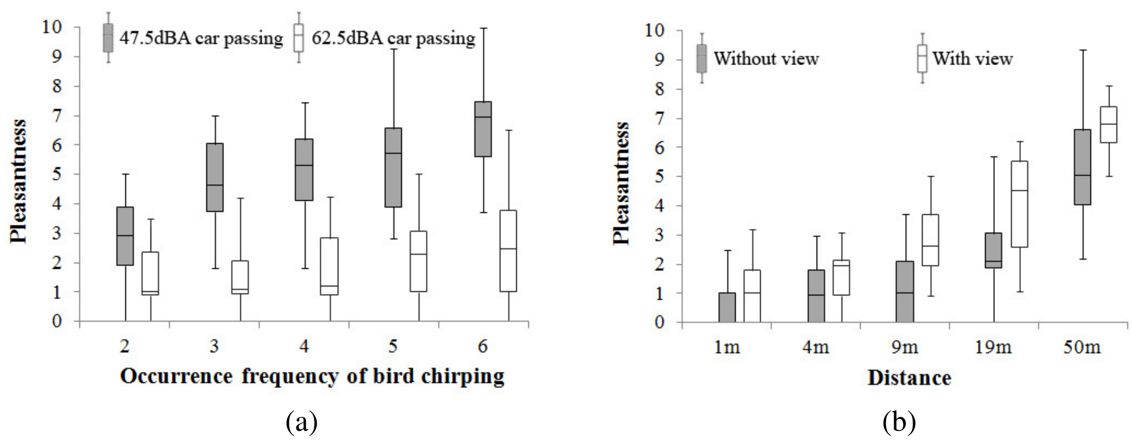

Figure 1. Box-and-Whisker Plots of the psychological evaluations of Pleasantness of the car traffic noise environments: (a) with different occurrence frequencies of birdsong (2, 3, 4, 5 and 6 times); (b) with and without view of greenery at distances of 1, 4, 9, 19 and 50 m from the road

3.1.2 Flyover aircraft noise and birdsong

To examine the influence of sound interaction between birdsong and aircraft noise, with consideration of loudness of aircraft noise, the mean values of four characteristics of the three acoustic stimuli of recorded aircraft noise were calculated, as shown in Table 1 Group B. The results of ANOVA analysis show that the mean differences of the four characteristics among the three acoustic stimuli of aircraft noise are all significant (p <0.00).

The one-way ANOVA shows the difference of 63.3 dBA with and without birdsong is only significant in Perceived Loudness. It can be seen that the aircraft noise with birdsong has much lower Perceived Loudness (4.7) than the one without birdsong (6.0), as shown in Table 2. However, the differences in other three characteristics are not significant.

The acoustic stimuli of "63.3 dBA with birdsong" and "44.2 dBA with birdsong" are significantly different in Naturalness, Annoyance and Pleasantness (p <0.00). An increase of 2.5 in Naturalness, an increase of 2.1 in Pleasantness and a decrease of 2.2 in Annoyance are resulted by a sound pressure level decrease of 16.8 dBA. Therefore, attenuating the sound pressure level of aircraft noise is still essential for the improvement of soundscape quality.

3.2 Effects of visual stimuli

Table 2 illustrates all the mean scores of the psychological evaluation of the four soundscape characteristics in Group C and D, which indicates that evaluation of soundscape quality of the car traffic noise and water sounds was significantly influenced by the visibility of greenery and water features.

Table 2: Mean values of the psychological evaluations of the four soundscape characteristics of car traffic noise and flyover aircraft noise with birdsong.

		Perceived Loudness		Naturalness		Annoyance		Pleasantness	
	With view?	No	Yes	No	Yes	No	Yes	No	Yes
Distance of the perceiver from road Group C)	1 m	8.8	8.9	1.5	1.8	8.2	7.9	0.5	0.9
	4 m	7.4	8.2	1.9	2.1	6.9	6.8	1.0	1.6
	9 m	6.6	7.0	2.3	3.1	6.0	6.5	1.3	2.6
	19 m	5.3	5.4	4.1	4.5	4.2	4.8	2.4	4.0
	50 m	2.4	2.7	6.3	6.5	1.7	1.8	5.5	6.7
Water features (Group D)	Big fountain	4.2	4.3	1.9	4.3	3.5	3.5	1.7	3.2
	Peace Garden	4.1	4.1	5.7	6.0	1.9	1.6	5.0	6.6
	Bakers Pool	3.1	3.3	4.9	4.8	2.0	2.0	3.9	4.7
	Howard Street	2.8	3.0	6.0	5.9	1.3	1.5	5.5	6.5
	Steel Barrier	4.5	4.2	5.2	4.1	1.7	2.9	4.1	3.8

3.2.1 Visibility of greenery

To initially investigate the effects of visibility of greenery on soundscape quality evaluation, five acoustic stimuli in Group C were played with and without the pictures of in-situ scenes. The one-way ANOVA shows significant differences among the five stimuli with the pictures of in-situ scenes in Perceived Loudness [$F(4, 145) = 130.46$, $p = 0.000$], Naturalness [$F(4, 145) = 34.54$, $p = 0.000$], Annoyance [$F(4, 145) = 64.02$, $p = 0.000$] and Pleasantness [$F(4, 145) = 34.07$, $p = 0.000$]. In Wilcoxon-signed rank tests, only Pleasantness of the traffic noise at distances of 9, 19 and 50 m have significant differences between the with- and without-views conditions ($p < 0.05$).

Table 2 illustrates the mean values of the four characteristics of the road traffic noise and birdsong environment at distances of 1, 4, 9, 19 and 50 m with and without the pictures of in-situ scenes being played. As shown in Table 2, Pleasantness showed an increase of 1.3 at a distance of 9 m, an increase of 1.6 at 19 m and an increase of 1.2 at 50 m when the in-situ scenes were played. Figure 1(b) further illustrates the statistical distribution of the evaluation scores of Pleasantness with and without the in-situ scenes.

3.2.2 Visibility of water features

The soundscape characteristics of the five water features in Sheffield are diverse, as shown in Table 2 Group D. The results of ANOVA analysis further show that the mean difference of Pleasantness among the five water sounds is significant [$F(4, 145) = 15.03$, $p < 0.00$]. Naturalness of the five water sounds is not high, from 1.9 to 6.0 (4.7 in average) (see Table 2), and the standard deviation is 1.37. A two-tailored Bivariate Correlation analysis and linear regressions were carried out to reveal the relationships between each two of the four characteristics.

For the water sounds, the visibility of the sound sources has little influence on Perceived Loudness, with a maximum difference of 0.3, whereas it can increase the Pleasantness of water sounds. For example, the Pleasantness of Peace Gardens is 1.6 higher with view than without view, with $p < 0.05$.

Among the five water features, only the visibility of the Steel Barrier decreases the soundscape quality of its water sound, e.g., the increase of 1.2 in the Annoyance and the decrease of 0.3 in the Pleasantness (see Table 2). It might because that the appearance of steel is not favourable or natural (4.1) for the participants. The big fountain in the Sheaf Square has the most significant improvement of Naturalness with view (from 1.9 to 4.3), as shown in Table 2, which indicates the important role of additional visual information in auditory perception.

3.3 Narrative evaluation

The interview provides a good understanding of the experiment results and shows what has been considered in the psychological evaluation by the participants.

When the participants expressed how the sounds feel, they mentioned their life experience, e.g. *"I have **experience of living in a very annoying traffic noise environment** when I was a child, so I am very sensitive to the traffic noise. I feel the sounds are rather annoying.", "I like the sounds of aircraft which makes me feel **I would have a long trip**, so I marked the sound with 1 for pleasant, although it is loud…", "I prefer the **quietness**. I like the **birdsong**. When I heard **loud birdsong**, I think it is more natural. Maybe because I was born in countryside, I like the natural environment."*

The participants mentioned the information they obtained by hearing, which influenced their judgements, e.g. *"I heard traffic sounds. Some are **pretty close** and some are **of a distance**.", "I think the **water sounds** and the sounds with **pure birdsong** or **birdsong with distant traffic noise** are pleasant.", "I feel some traffic noise is really **annoying**. Someone recorded it **quite close to road**. I think the **distant traffic noise** is better.", "The **traffic noise** is not pleasant and I do not like the **events of traffic**. Some people didn't drive the cars in **a proper behaviour**."*

The scenes of the greenery and water features did influence the soundscape quality evaluation by multisensory attention, for example, *"**With pictures**, I feel it is better.", "I cannot **tell t**he fountain sounds if I did not **see the pictures**.", "I feel it is much better when I can **see the pictures of the sound scene**. When I can **see green**, I did not **pay much attention** to the traffic noise. The picture **attracted most of my attention**."*

The participants explained what factors result in the low soundscape quality, e.g. *"The sounds which are **variable** is **more annoying**, such as the sounds with **loud traffic at the end**.", "I feel uncomfortable with **low frequency sounds**.", "I dislike the **constant** water sounds.", "I do not feel the sounds are annoying unless it is **very loud**."*

Birdsong is believed as a natural soundmark and pleasant sound in a common sense, but the soundscape quality of water features are influenced by diverse factors. For example, *"I love **birdsong** very much; **no matter how loud it is or how many birds I can hear**."*, "*…When I heard louder birdsong, I feel I am **close to nature**, while when the birdsong is not that loud, I feel I am **further from nature***.", *"I do like the **bird chirping**, which makes me feel it is pleasant. I prefer **birdsong** to **water sounds**.", "I like the water sound which is **low running**, and also the birdsong.", "I like the **birdsong** in **quiet environment** and the **sound of the fountain with colourful piles**."*

The negative feedback of experiment settings were more on the difference in loudness between the sounds heard in the lab and the real life. For example, *"The sounds are **similar** to what I hear in daily life, but some of the traffic sounds are **louder**.", "I think some recorded traffic noise is **louder** than what I heard before."*

4. Conclusions and discussions

This study aimed to explore how significantly sound interaction and visual stimuli can influence soundscape quality evaluation in terms of four soundscape characteristics, i.e. perceived loudness, naturalness, annoyance and pleasantness, using psychological listening experiments. A key finding is that the sound interaction between narrow-band (birdsong) and wide-band sounds (traffic noise and flyover aircraft noise) with meaning in daily life significantly influences the soundscape quality evaluation in real life, which provides concrete evidences for the phenomena of "informational masking" in soundscape. The visual stimuli, which acts as information provider, also has an important role in the soundscape quality evaluation through multisensory attention. More details will be presented in ICSV24.

After a long history of noise control as the main consideration in sound environment assessment, emerging soundscape management, which is human-perception-centred, attract more and more attention from multidisciplinary. The research results are meaningful for the integrated design practice on soundscape and landscape due to the crucial role of visual-aural interaction on soundscape assessment, especially for the areas vulnerable to the intrusion of urban noise. The landscape features, such as green area and water features, with both natural sounds and scene, have been believed to be rich in the characteristics necessary for restorative experience. More popular and desirable sound environment can be achieved by soundscape management.

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