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Effects of adding natural sounds to urban noises on the perceived loudness of noise and soundscape quality

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ABSTRACT

Introducing pleasant natural sounds to mask urban noises is an important soundscape design strategy to improve acoustic comfort. This study investigates the effects of signal-to-noise ratio (SNR) between natural sounds (signal) and the target noises (noise) and their temporal characteristics on the perceived loudness of noise (PLN) and overall soundscape quality (OSQ) through a laboratory experiment. Two types of urban noise sources (hydraulic breaker and traffic noises) were set to A-weighted equivalent sound pressure levels (SPL) of 55, 65, and 75 dB and then augmented with two types of natural sounds (birdsong and stream), across a range of SNRs. Each acoustic stimulus was a combination of noise and natural sound at SNRs from –6 to 6 dB. Averaged across all cases, the subjective assessment of PLN showed that augmenting urban noise separately with the two natural sounds reduced the PLN by 17.9%, with no significant differences found between the birdsong and stream sounds. Adding natural sounds increased the OSQ by on average 18.3% across the cases, but their effects gradually decreased as the noise level increased. The OSQ of the birdsong and stream sounds were similar for traffic noise, whereas the stream sound was rated higher than the birdsong for the breaker noise. The results suggest that increasing the dissimilarity in temporal structure between the target noise and natural sounds could enhance the soundscape quality. Appropriate SNRs were explored considering both PLN and OSQ. The results showed that the SNR of –6 dB was desirable when the A-weighted SPL of the noise rose to 75 dB.

Keywords: Acoustic environment, Auditory masking; Natural sounds; Soundscape; Traffic noise; Construction noise

1. INTRODUCTION

Traditional noise management approaches are focused on the reduction of acoustic energy of unwanted sounds in the sonic environment, thereby treating sound as a waste to be removed or reduced (Brown, 2010). In outdoor environments, conventional noise mitigation measures, such as tall noise barriers, are usually undesirable or impractical to enhance the perceived acoustic quality. In contrast, the soundscape approach treats sound as a resource with a focus on sounds of preference in the context of a place (Kang and Schulte-Fortkamp, 2016). Soundscape practitioners have probed into the possibility of adding pleasant sounds to achieve similar effects as traditional noise reduction. Pleasant sounds have long been viewed as a method to drownout unwanted sounds (e.g., mechanical and man-made sounds) through the lenses of traditional psychoacoustic auditory masking (American National Standards Institute, 2013).

In an attempt to account for phenomena beyond which could be attributed to traditional auditory masking, soundscape studies have gradually adopted two categories of auditory masking: energetic masking (EM) and informational (or attentional) masking (IM). The former, EM, models after the definition of traditional auditory masking, which refers to the physical process at the inner ear where a target sound (usually unwanted noise in soundscape studies) is rendered inaudible (complete masking), or less audible (partial masking), by a masker excited at similar time-frequency locations (Gelfand, 2017; Kidd et al., 2008). The asymmetric nature of EM (low-frequencies mask high-frequencies more effectively than vice versa) increases the difficulty in masking high-energy, low-frequency transportation noise using natural sounds that are usually of higher frequencies (Gelfand, 2017; Nilsson et al., 2014a). Even if the maskers satisfy the spectral requirements, such as using waterfall sounds with high-energy at low-frequencies, subjective test results have shown that waterfall sounds are the least preferred type of masker over other types of water sounds (Galbrun and Ali, 2013; Jeon et al., 2010).

Therefore, relying on the principles of EM alone proves to be ineffective in improving soundscape quality.

The latter, IM, has been defined as masking that occurs beyond which could be attributed to EM due to higher-level central processes of the auditory system, thus prompting various definitions (Gelfand, 2017; Kidd et al., 2008; Watson, 2005; Westermann and Buchholz, 2015). The way IM is described in soundscape studies revolves around the concept of saliency (or noticeability) of sounds, which is used to refer to the degree to which an event stands out from the sonic environment (Nilsson et al., 2014b; Oldoni et al., 2013). For instance, even though natural sounds, such as birdsong or water sounds, are unable to energetically mask low-frequency urban noises, they can still improve the soundscape quality by reportedly attracting people's attention away from the urban noise (the target sound) and eventually evoking pleasant perceptual reactions to the natural sounds (e.g., appreciation of water sounds or birdsong).

Studies attributing the observed phenomena to IM, have adopted an indirect approach rather than a direct measure of auditory attention (Kaya and Elhilali, 2017, 2014). These studies have investigated the effect of auditory masking on soundscape evaluations through the addition of water sounds (Axelsson et al., 2014; Galbrun and Ali, 2013; Jeon et al., 2010) and birdsong (De Coensel et al., 2011; Hao et al., 2016; Hong and Jeon, 2013) to traffic noise. In particular, the signal-to-noise ratio (SNR) between natural sounds and target noise (De Coensel et al., 2011; Galbrun and Ali, 2013; Jeon et al., 2010) and the temporal characteristics of both target noise and natural sound types (De Coensel et al., 2011; Hao et al., 2016; Rådsten Ekman et al., 2015) were found to be key acoustical factors in the subjective assessments of the soundscape. However, few studies have explored the appropriate SNRs in terms of the largest reduction in perceived loudness and increment in overall soundscape quality for both natural sounds and noise with different spectro-temporal characteristics (De Coensel et al., 2011; Jeon et al., 2010).

Therefore, this study explores the effect of key acoustical factors, namely the SNR between natural sounds and the target noises and the spectro-temporal nature of both natural sounds and noise, on the subjective assessment of soundscapes. Two types of natural sounds (i.e., water and birdsongs) and noise (i.e., heavy road traffic and hydraulic breaker) were selected as the "maskers" and target noises respectively, accounting for a large contrast in spectro-temporal characteristics. Assessments in terms of the perceived loudness of noise and soundscape quality were evaluated at various SNRs and background target noise levels through a subjective auditory experiment in a controlled laboratory setting.

Specifically, three research questions are addressed in this study: (1) Are there significant differences between adding birdsong and water sounds in a reduction in perceived loudness and improvement of soundscape quality for both steady (i.e., heavy traffic) and impulsive (i.e., hydraulic breaker) urban noises? (2) Is the effect of the SNR between natural sound and target noise significant across different background noise levels when judging PLN and OSQ? (3) Are appropriate SNRs and natural sound types significantly different for different noise types and background noise levels? The findings of the experiments pertaining to the research questions, together with the limitations of this study, will be discussed in the context of soundscape design by natural sound augmentation.

2. METHOD

2.1. Participants

A total of 68 paid participants (43 males and 25 females) were recruited for the experiment; 37 participants were undergraduate students who were remunerated for their time, whereas 31 other participants were non-student voluntary participants. All participants were non-acoustic experts and the majority ethnic group of the participants was Chinese (62 Chinese, 3 Indians, 1 Malays, 1 Filipino, and 1 Myanmar). The participants' ages ranged from 20 to 65 years old

(M_{age} = 31.7 and SD_{age} = 12.0), and the proportion of participants in their 20s, 30s and >40s were 57.4%, 20.6%, and 22.0% respectively.

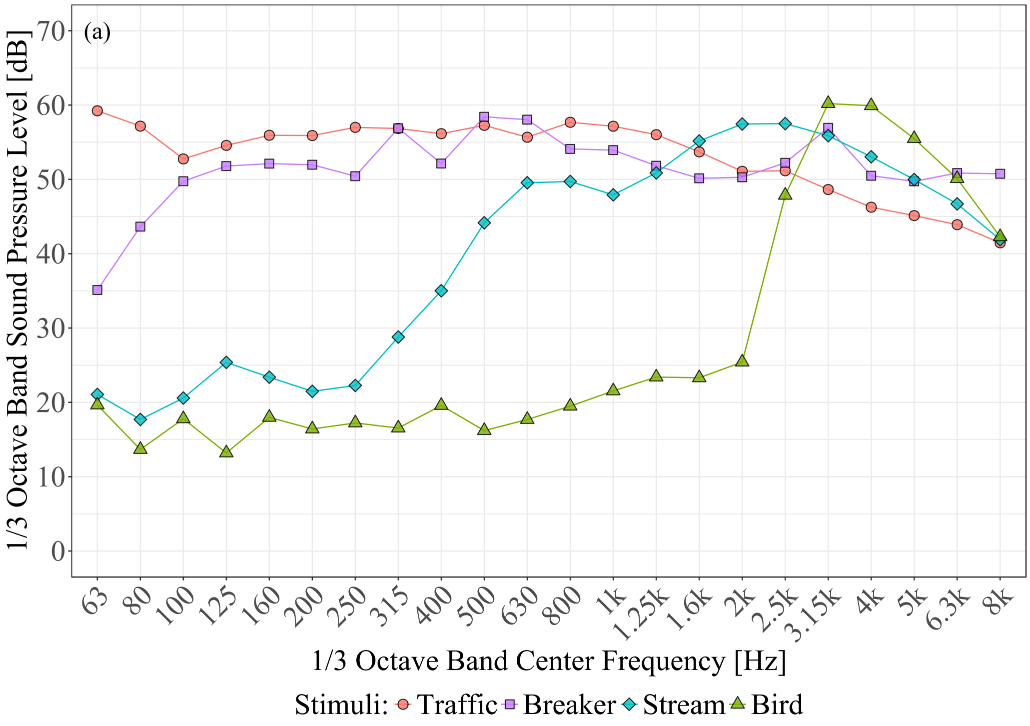
Hearing tests were conducted using an audiometer (Interacoustics AD629, Denmark) and the results showed that all participants had normal hearing for all the tested frequencies (0.125, 0.5, 1, 2, 3, 4, 6, and 8 kHz). Formal ethical approval (IRB-2017-07-025) to conduct this experiment was obtained from the institutional review board of the Nanyang Technological University, Singapore. Following ethical procedures, the participants were informed about this study via written information, and written consent was obtained for all the participants.

2.2. Stimuli

Due to increasing noise complaints caused by construction activities and road traffic in recent years (Jeon et al., 2010; Lee et al., 2015), two representative urban noise sources, road traffic and construction noise, were considered. The road traffic and hydraulic breaker noises were recorded from real urban environments using a microphone (G.R.A.S. Type 40-PH CCP Microphone, Denmark) via a data acquisition device (National Instruments NI 9234, USA). The road traffic noise was recorded 35 m away from the closest lane of the Pan Island Expressway (2 × 4 lanes) in Singapore. The hydraulic breaker noise was chosen as it was judged as one of the most annoying construction machine noises in a previous survey (Lee et al., 2019, 2015). The hydraulic breaker noise was recorded 10m away in the absence of other construction noises. The 1-min A-weighted SPL of the recorded traffic and breaker noises were 68.5 dB and 88.3 dB, respectively.

Guided by previous findings (Hong et al., 2017b), two mono recordings of natural sounds that were reportedly pleasant were chosen: a birdsong (sparrow) and a water sound (stream) selected from the Korean Broadcasting System’s (KBS) archive of natural sounds. In the auditory experiment, 10-s mono audio samples of the urban noise and natural sounds were excerpted from the recordings to avoid spatial unmasking effects that occurred in previous studies (Hong and Jeon, 2013; Jeon et al., 2012).

The sound pressure levels (SPL) of the stimuli are plotted as a function of 1/3 octave bands from 63 Hz to 8 kHz in Fig. 1(a). For comparison, all the stimuli were normalized to an A-weighted SPL of 65 dB, with the A-weighting being performed according to the ANSI S1.42 standard. The road traffic and breaker noises had almost constant SPL at all frequency ranges except below 100 Hz. The stream sound contained higher energy from 500 Hz to 4 kHz. The birdsong was dominated by high-frequency components, especially above 2 kHz.



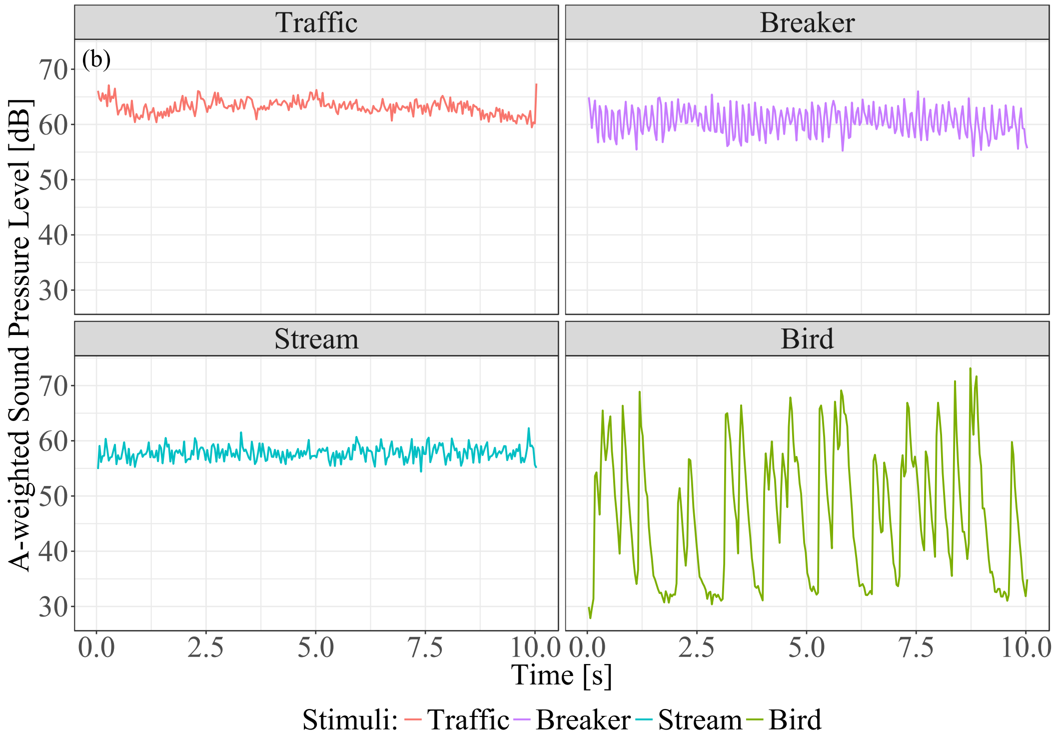


Fig. 1. Acoustical characteristics of the traffic (—), breaker (—), stream (—), and bird (—) stimuli **(**10-s A-weighted sound pressure level at 65 dB) in: (a) 1/3 octave band spectra and (b) A-weighted sound pressure level as a function of time.

Figure 1(b) shows the A-weighted SPL of the acoustic stimuli as a function of time; impulse time weighting (35 ms) specified in IEC-61672:2013 was applied to clearly display temporal variability of the stimuli. The time-domain plots of the stimuli reveal that the traffic noise and stream sound were relatively stationary with low temporal variability, while the breaker noise and birdsong were non-stationary sounds.

Psychoacoustic parameters of the stimuli, namely *loudness*, *sharpness*, *roughness*, and *fluctuation strength*, were calculated with a commercial software package (ArtemiS Suite, HEAD acoustics GmbH, Germany). The time-varying *loudness*, representing the magnitude of an auditory sensation, was calculated according to ISO 532-1 (2017). *Sharpness*, which is the sensation value of the amount of high-frequency content, was calculated based on DIN 45692

(DIN 45692, 2009). In addition, *roughness* and *fluctuation strength,* which quantify the subjective perception of amplitude modulation of a sound, were calculated as proposed by Zwicker and Fastl (Fastl and Zwicker, 2006). The modulation frequencies of *roughness* and *fluctuation strength* were 70 Hz and 4 Hz, respectively.

The calculated psychoacoustic parameters for individual stimuli (normalized to an A-weighted SPL of 65 dB) are presented in Table 1. Despite the SPL normalization, the time-varying *loudness* of the birdsong was lower than the other stimuli as it was non-stationary. The birdsong also exhibited the highest *sharpness* value among the stimuli, followed in order by the stream sound, breaker noise, and traffic noise. In terms of *roughness*, the breaker and stream sounds had higher values than the traffic and birdsong. The birdsong and breaker sounds showed higher *fluctuation strength* values than the traffic and stream sounds.

Table 1. Psychoacoustic parameters of each stimuli **(**10-s A-weighted sound pressure level at 65 dB)

Type	*Loudness* (sone)	*Sharpness* (acum)	*Roughness* (asper)	*Fluctuation Strength* (vacil)
Traffic	23.80	1.40	0.05	0.03
Breaker	24.50	1.83	0.14	0.29
Bird	13.00	2.63	0.05	0.19
Stream	19.30	1.92	0.20	0.02

As described in ISO 1996-1 (2016), the temporal structure of the traffic noise can be characterized as a constant continuous sound. Meanwhile, the breaker noise can be described as a highly impulsive sound, having continuous burst sounds with a duration of less than one second. The impulse rate of the breaker sound was 6.9 Hz. For the natural sounds investigated, the bird song can be considered intermittent, whereas the stream sound can be temporally characterized as a constant continuous sound.

The four psychoacoustic parameters for the combined stimuli as a function of SNR are displayed in Figs. 2(a-h). The *loudness* of the combined stimuli increased as the SNR increased, as shown in Fig. 2(a) and (b). The *loudness* values of both urban noises with stream sounds were slightly larger at positive SNRs than those with birdsong.

The *sharpness* values of the traffic noise with both natural sounds exhibited a similar increasing trend to *loudness*, where combination with birdsong exhibiting relatively higher values than with stream sound, as shown in Fig. 2(c). Whereas the *sharpness* of breaker noise with birdsong also increased with SNR, the *sharpness* of the breaker noise with stream sound remained constant, as shown in Fig. 2(d).

Although the *roughness* values of traffic noise with both natural sounds also increased with SNR, the increase was far greater with stream sound than birdsong, as shown in Fig. 2(e). For breaker noise with birdsong, the *roughness* slightly decreased with SNR, whereas the *roughness* of breaker noise with stream sound increased with SNR, as shown in Fig. 2(f).

The *fluctuation strength* values of the traffic noise were unaffected with the addition of stream sound, whereas *fluctuation strength* increased with SNR when traffic was combined birdsong, as shown in Fig. 2(g). Finally, the *fluctuation strength* values decreased with SNR when the breaker noise was combined with both natural sounds, as shown in Fig. 2(h) However, the *fluctuation strength* of the breaker noise with stream sound were relatively lower than with the birdsong.

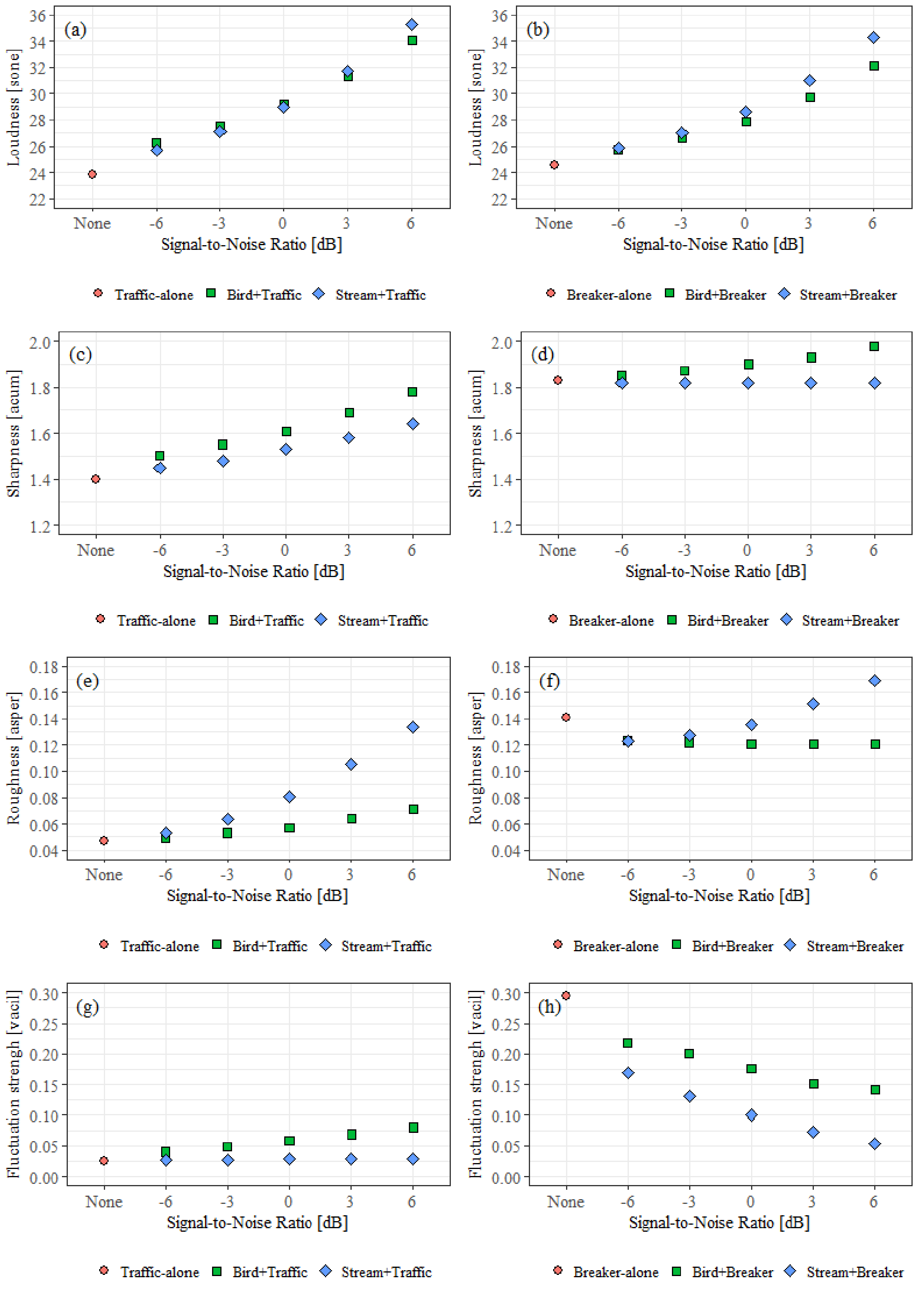

(a)
(b)
Loudness [sone]
36
34
32
30
28
26
24
22
Sharpness [acum]
(c)
(d)
2.0
1.8
1.6
1.4
1.2
Roughness [asper]
(e)
(f)
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
Fluctuation strengh [vacil]
(g)
(h)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
None
-6
-3
0
3
6
Signal-to-Noise Ratio [dB]
● Traffic-alone
■ Bird+Traffic
◆ Stream+Traffic
● Breaker-alone
■ Bird+Breaker
◆ Stream+Breaker

Fig. 2. Psychoacoustic *loudness*, *sharpness*, *roughness*, and *fluctuation strength* as a function of SNR (−6 dB to 6 dB) for both traffic (a, c, e, g) and breaker noise (b, d, f, h). The traffic and breaker noises at 65 dB (10-s A-weighted) were included for comparison to the respective combined cases of bird+traffic, stream+traffic, bird+breaker and stream+breaker.

2.3. Experimental design

The laboratory experiment examined the effect of SNR on the evaluation of urban noises augmented with natural sounds at various noise levels. Similar to previous studies (Galbrun and Ali, 2013; Jeon et al., 2010), the SNRs were designed based on A-weighted equivalent SPLs of the stimuli with fast time weighting (125 ms). For an appropriate representation of noise levels in the urban environment (Hong and Jeon, 2015; Jeon et al., 2010; Morillas et al., 2005), the traffic and breaker machine noises were set to three levels in 10 dB steps (55, 65 and 75 dB) so that six individual "noise-alone" cases were created (traffic noise × 3 noise levels + breaker noise × 3 noise levels = 6 noise-alone cases). Each of the noise-alone cases was combined with each of the natural sounds at different SNR levels to yield combined-sound cases. Similar to previous studies (Galbrun and Ali, 2013; Jeon et al., 2010), in the combined-sound cases, the SNR varied from -6 dB to 6 dB in intervals of 3 dB for each of the three noise levels to yield 60 acoustic stimuli (2 types of noise × 3 noise levels × 5 SNRs × 2 types of natural sounds). In total, 66 stimuli (6 noise-alone cases + 60 combined-sound cases) were used in this auditory test.

Both the perceived loudness of noise and soundscape quality were evaluated for all 66 stimuli. "Perceived loudness" in this study was defined as a subjective overall impression of auditory loudness, which is distinguished from the notion of loudness as an objective measure in the unit, sone, in psychoacoustics (Zwicker and Fastl, 2013). The perceived loudness of noise (PLN) for both the road traffic noise and breaker noise was assessed by varying the SNR between the noises and natural sounds using the magnitude estimation method (Gescheider, 1997), which has been applied in previous studies to quantify the impression of the loudness of environmental sounds (Aylor and Marks, 1976; Bolin et al., 2014; Nilsson et al., 2010).

A fixed-number magnitude estimation method was employed, where a standard stimulus was given to the participant as a reference, and the reference was assigned a fixed value for the numerical response.

Participants rated the PLN for all subsequent stimuli relative to this reference stimulus. The PLN for all subsequent stimuli was evaluated relative to this reference stimulus. The traffic noise at 65 dB was set as the reference with an assigned a fixed value of “100” for its perceived loudness. The participants were asked to assign numbers to all other stimuli representing the ratio of the PLN relative to the reference. For instance, if the perceived loudness of traffic noise or breaker noise in the next stimulus was twice as loud, the participant would assign it a value of “200”. On the other hand, if it was half as loud, a value of “50” would be assigned.

The overall impression of the soundscape, which included both the target noise and natural sounds, was evaluated to measure the perceived soundscape quality. Overall soundscape quality (OSQ) is one of the most important soundscape descriptors, and is defined as the hedonic value of sound in context (Aletta et al., 2016). In addition, subjective assessment regarding soundscape quality has been found to be consistent and reliable even across different cultural backgrounds (Jeon et al., 2018). The participants were instructed to imagine that they were sitting in an urban outdoor area such as a park, close to an expressway, and were then asked to assess the OSQ for each stimulus using an 11-point scale (0: extremely bad and 10: extremely good).

2.4. Procedure

The acoustic stimuli were presented to the subjects in random order through headphones (Beyerdynamic Custom One Pro, Germany) connected to a sound card (Creative SoundBlaster E5, Singapore). The 10-s A-weighted SPL of each stimulus was calibrated using a head and torso simulator (Brüel & Kjær 4128-C, Denmark). The acoustic stimuli were then equalized through inverse filtering with the measured headphone transfer function (HPTF) of the headphone used, to prevent any changes to the frequency characteristics of stimuli due to the headphones. Previous studies (Hong et al., 2019; Sudarsono and Sarwono, 2018) have validated that acoustic reproduction using a headphone can exhibit sufficient fidelity for soundscape evaluation in terms of ecological validity.

The auditory test was performed in a sound testing room with an A-weighted background noise level of 28 dB. A graphical user interface (GUI) developed using MATLAB 2016a (MathWorks, USA) was used to conduct the test. The GUI developed for this experiment allowed the participants to play each stimulus as many times as required to provide sufficient time for more accurate evaluation of PLN and OSQ.

Before the main experiment, a training session was conducted to familiarize the participants with the procedure of the magnitude estimation method. The experiment consisted of two sessions: 1) traffic noise with natural sounds, and 2) breaker noise with natural sounds. Each session took approximately 20-30 minutes, and the break time between the sessions was at least 15 minutes to relieve boredom and fatigue (Schatz et al., 2012).

2.5. Data analysis

Repeated measures analysis of variance (RM ANOVA) tests were performed to investigate the within-subjects effects of SNR and types of natural sound on PLN and OSQ. There were six levels for the independent variable ‘SNR’ including the noise-alone case and the five SNR cases. The independent variable ‘type of natural sound’ had two levels, namely the birdsong and stream sound. Mauchly's test of sphericity was conducted to examine the assumption of sphericity. When the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied to correct the degrees of freedom of the *F*-distribution and the corresponding *p*-values are reported. The column for ${\eta_p}^2$ indicates partial eta squared values as a measure of an effect size of each independent variable.

In RM ANOVA tests, post-hoc comparisons were conducted using the Bonferroni correction. The Bonferroni correction is a well-known adjustment to significance levels that reduces the probability of obtaining false-positive results (type I errors) when multiple pair-wise tests are performed. Significance levels (*p*-values) were corrected by dividing them by the number of dependent comparisons to be made. Partial eta-squared (n_p^2) values were also reported as an effect size measure. All statistical analyses were performed using the statistical software package SPSS (version 23.0, IBM, USA).

3. RESULTS

3.1. Reduction in perceived loudness of noise

All magnitude estimates were geometrically averaged for each acoustic stimulus across the participants. A geometric mean is commonly used due to its efficacy in describing characteristics of psychophysical functions, and can be used to provide an unbiased estimate of the expected value of the logarithms of the magnitude estimates. The geometric mean values of PLN for the noise-alone cases and combined-sound cases are plotted on the ordinate against SNR on the abscissa, as shown in Fig. 3. The ordinate is a logarithmic scale because magnitude estimation is based on a ratio scaling method (Aylor and Marks, 1976; Nilsson et al., 2010).

For each 10 dB increase in noise SPL, the PLNs for the traffic and breaker noise-only cases were approximately doubled. The breaker noise was perceived as slightly louder than the traffic noise when the noise levels were 55 and 65 dB. Adding the two natural sounds reduced the PLNs of traffic and breaker noises at all noise levels.

The data sets of subjective responses were split into six sub-datasets according to each of the three target noise levels of each of the two noise types. A two-way RM ANOVA was conducted for each sub-dataset to examine the effects of SNR and natural sound types on the PLN. Table 2 summarizes the output of the RM ANOVA analysis for six sub-datasets informing whether SNR, types of natural sounds, and their interaction have statistically significant effects on PLN.

Table 2. Summary of RM ANOVA for the perceived loudness of noise.

Noise type	Noise level	Factors	df_1	df_2	F	*p*	η_p^2
Breaker	55 dB	SNR [a]	2.9	193.7	30.80	< .001	0.31
		Type of natural sound	1.0	67.0	2.29	0.14	0.03
		Interaction [a]	3.4	225.6	1.53	0.22	0.02
	65 dB	SNR [a]	3.2	207.1	36.65	< .001	0.36
		Type of natural sound	1.0	64.0	3.72	0.06	0.05
		Interaction [a]	3.8	240.6	3.31	0.07	0.05
	75 dB	SNR [a]	1.9	128.0	36.92	< .001	0.36
		Type of natural sound	1.0	67.0	0.39	0.53	0.01
		Interaction [a]	3.1	205.9	1.19	0.28	0.02
Traffic	55 dB	SNR [a]	2.5	166.1	14.96	< .001	0.18
		Type of natural sound	1.0	67.0	1.13	0.29	0.02
		Interaction [a]	3.6	238.8	1.05	0.39	0.02
	65 dB	SNR [a]	2.2	142.1	27.78	< .001	0.30
		Type of natural sound	1.0	66.0	0.09	0.77	0.00
		Interaction [a]	2.2	147.2	3.98	0.50	0.06
	75 dB	SNR [a]	2.1	131.4	23.25	< .001	0.27
		Type of natural sound	1.0	64.0	1.34	0.25	0.02
		Interaction [a]	3.6	233.2	2.80	0.09	0.04

[a] Assumption of sphericity was violated and Greenhouse–Geisser correction was applied.

The main effects of SNR on PLN were statistically significant across the noise types and noise levels ($p < 0.001$), whereas the mean differences in PLN between adding birdsong and stream sounds were statistically insignificant ($p > 0.05$) across the six sub-datasets. This finding implies that the intensity of the natural sound is a critical factor in determining the reduction of PLN rather than its type, at least for the urban noise stimuli tested. Significant interactions between the SNR and type of natural sounds were not found, indicating that the effects of SNR and type of natural sounds are statistically independent.

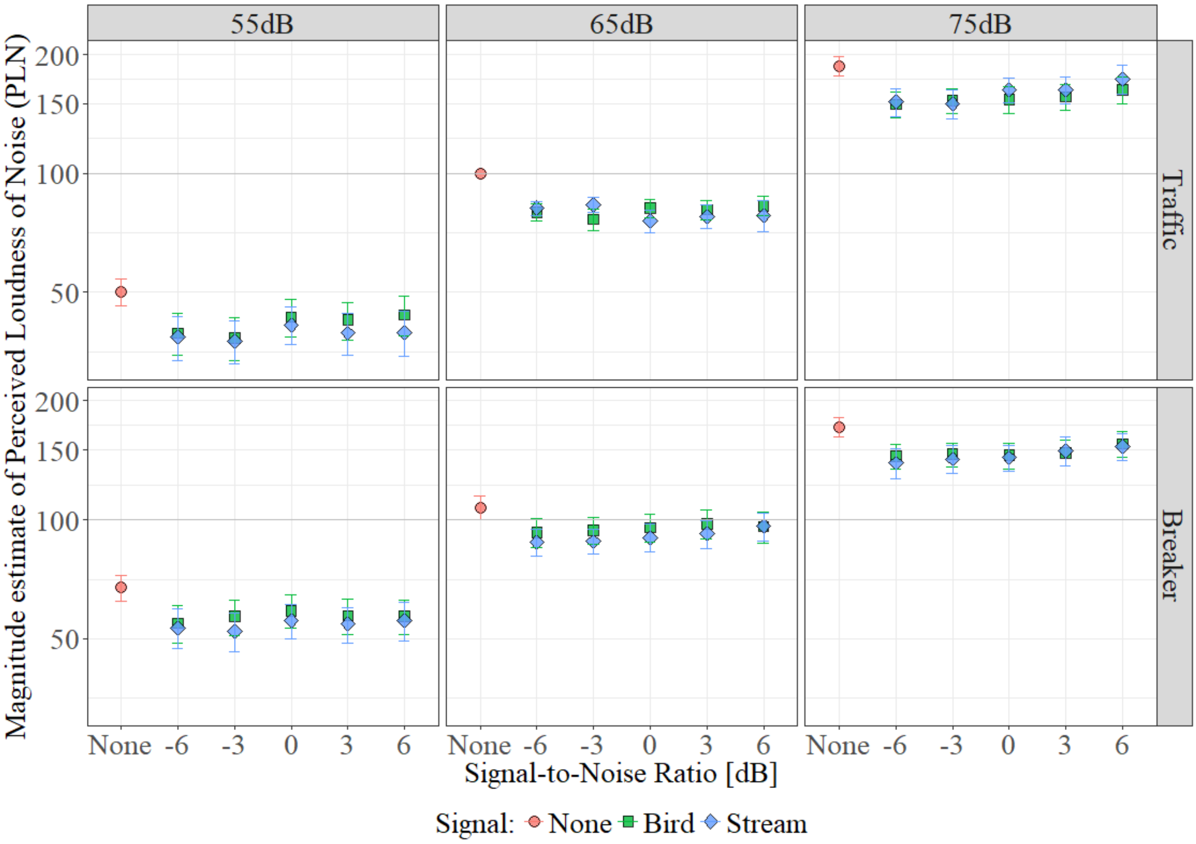


Fig. 3. Geometric mean values of PLN as a function of SNR. Error bars indicate 95% confidence intervals. The perceived loudness of the reference (Traffic noise of 65 dB) was assigned a value of “100”. The columns and rows in the faceted plots indicate three different noise levels and two different noise types, respectively.

Post-hoc comparisons were conducted using the Bonferroni correction to examine the differences in PLN across SNRs for each sub-dataset. The results showed that the PLN of both the breaker and traffic noises significantly decreases for every SNR across the three different noise levels ($p < 0.05$) compared to noise-only cases, indicating that adding natural sounds in the range of SNRs from -6 dB to 6 dB can reduce the perceived loudness of traffic and breaker noises.

The reduction in PLN across SNRs was also compared at the three different noise levels. When the traffic noise levels were 55 dB and 65 dB, statistically significant differences in the reduction in PLN were not observed across the SNRs form -6 dB to 6 dB. However, the PLN of traffic noise of 75 dB at an SNR of 6 dB was significantly greater than those at the other SNRs ($p < 0.05$). There were no significant differences in PLN across the SNRs when the breaker noise level was 55 dB. When breaker noise levels were 65 dB and 75 dB, there were no significant differences in PLN among the SNRs (≤ 0 dB), whereas PLNs at the SNRs of 3 dB and 6 dB were significantly higher than PLNs at the lower SNRs (≤ 0 dB). The findings suggest that when target noise levels are higher than 65 dB, introducing natural sounds with higher SPL than the target noise level could diminish the PLN reduction effect of natural sounds, because it increases the overall SPL of the sound environment.

To quantify the PLN reduction effect of natural sounds, reduction ratios of PLN were calculated. The reduction ratio of PLN for each stimulus was obtained by calculating the ratio of change in PLN between the noise-alone and combined-sound cases to the PLN of the noise-alone case. For instance, if the PLN of traffic noise at 65 dB is 100 and the PLN of traffic noise at 65 dB changes to 70 by adding the bird song at an SNR of -3 dB, then the reduction ratio is calculated as 30% {[(100-70)/100] × 100, %}.

Figure 4 shows the reduction ratio of PLN for each case as the ordinate with SNR as the abscissa. Averaged across all cases tested, adding natural sounds decreases the PLN of traffic and breaker noise across the three different noise levels by approximately 17.9%. The PLN reduction effect of natural sounds tends to decrease with increasing SNR, except for the case where the traffic noise level was 65 dB. These results support the findings of previous studies that augmented natural sounds with similar or 3 dB less SPL as compared to the urban noise were evaluated as preferable (Galbrun and Ali, 2013; Jeon et al., 2010; You et al., 2010).

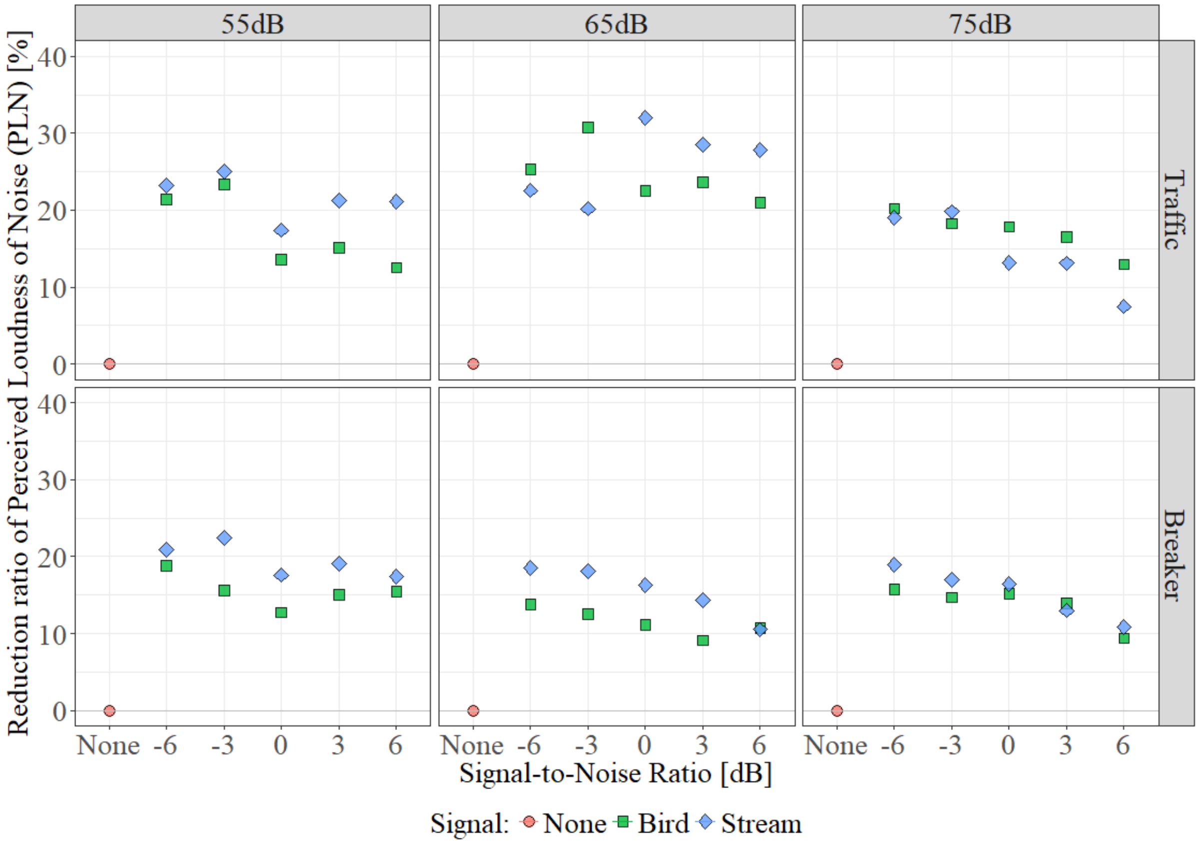


Fig. 4. Reduction ratio of PLN as a function of SNR. The columns and rows in the faceted plots indicate three different noise levels and two different noise types, respectively.

The PLN reduction effects of birdsong and stream sounds differed at different background target noise levels. For the traffic noise at 55 and 65 dB, the PLN reduction effect of the stream sound was greater than that of the birdsong, especially when the SNR was higher than 0 dB; whereas the PLN reduction effect of birdsong was similar or slightly better than the stream sound when combined with the traffic noise at 75 dB. For the breaker noise at 55 and 65 dB, the PLN reduction effect of the stream sound was also greater than those of birdsong across the

SNRs, whereas there were no significant differences in the reduction ratio of PLN between the bird song and stream sound when the breaker noise was at 75 dB.

3.2. Enhancement of overall soundscape quality

The OSQ scores as a function of SNR for the six sub-datasets of three noise levels (horizontal panels) and two noise types (vertical panels) are plotted in Fig. 5. For the noise-only cases, the OSQ scores gradually decreased as the target noise levels increased. Two-way RM ANOVAs were performed for the six sub-datasets (three noise levels × two noise types) to explore the effects of SNR and type of natural sounds (main effects and interactions) on the perceived soundscape quality. Table 3 shows the RM ANOVA results for the six sub-datasets.

The main effects of SNR on the OSQ scores were statistically significant for both the breaker and traffic noise across the three different noise levels. The main effect of the types of natural sounds, however, was not significant for traffic noise. In other words, there were no significant differences in OSQ scores between the birdsong and water sounds when they were augmented with the traffic noise. Interestingly, regarding the breaker noise, the main effects of natural sound types on OSQ scores were significant across the noise levels from 55 to 75 dB ($p < 0.05$), even though the effect size (n_p^2) for the types of natural sounds are smaller than those of SNR. Mean OSQ scores for the breaker noise with the stream sound were significantly higher than that with birdsong. This indicates that the stream sound could be a better natural sound for masking the breaker noise than the birdsong. Interaction effects between the SNR and type of natural sounds were not found for both the traffic and breaker noises.

Bonferroni post-hoc tests for SNRs were conducted to examine the differences in OSQ scores across SNRs. The results showed that introducing the birdsong or stream sound significantly increased the OSQ of both the breaker and traffic noises for every SNR across the three different noise levels as compared to the noise-only cases ($p < 0.05$).

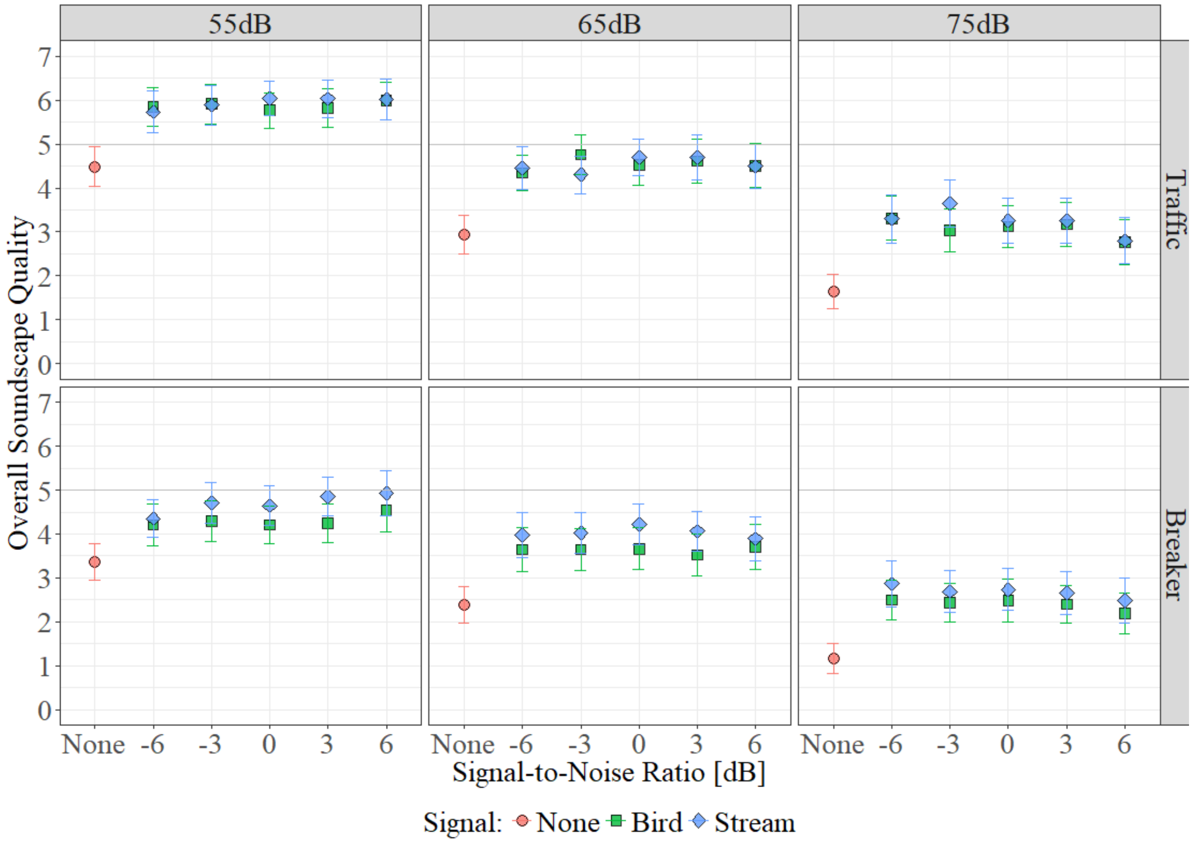


Fig. 5. Mean overall soundscape quality (OSQ) scores as a function of SNR. Error bars indicate 95% confidence intervals. The columns and rows in the faceted plots indicate three different noise levels and two different noise types, respectively.

However, unlike the PLN reduction ratio, the OSQ scores in most cases were invariant with SNR, which implies that the OSQ score might be less dependent on the SNR than the PLN. For the breaker noise, there were no statistically significant differences in OSQ scores across the SNRs, except that the OSQ score at an SNR of +6 dB was greater than that at SNRs of 0 dB and −6 dB ($p < 0.05$) when the breaker noise was 55 dB. These results demonstrate that higher natural sound levels than breaker noise levels could be favored in improving soundscape quality when the breaker noise level is low, whereas participants have little concerns about the natural sound level if the breaker noise level is higher than 65 dB.

Table 3. Summary of RM ANOVA for the overall soundscape quality

Noise type	Noise level	Factors	df_1	df_2	F	p	n_p^2
Breaker	55 dB	SNR [a]	2.7	184.2	33.38	< .001	0.33
		Type of natural sound	1.0	67.0	10.78	< .001	0.14
		Interaction [a]	3.1	207.9	3.23	0.07	0.05
	65 dB	SNR [a]	3.1	196.4	42.98	< .001	0.40
		Type of natural sound	1.0	64.0	6.42	0.01	0.09
		Interaction [a]	3.6	233.1	3.02	0.09	0.05
	75 dB	SNR [a]	2.3	154.0	36.94	< .001	0.36
		Type of natural sound	1.0	67.0	7.42	0.01	0.10
		Interaction [a]	3.1	209.9	1.35	0.25	0.02
Traffic	55 dB	SNR [a]	2.6	177.2	22.95	< .001	0.26
		Type of natural sound	1.0	67.0	0.30	0.58	0.00
		Interaction [a]	3.6	244.1	0.95	0.33	0.01
	65 dB	SNR [a]	2.7	178.9	37.65	< .001	0.36
		Type of natural sound	1.0	66.0	0.04	0.85	0.00
		Interaction [a]	2.9	194.0	2.66	0.11	0.04
	75 dB	SNR [a]	2.7	173.5	35.21	< .001	0.35
		Type of natural sound	1.0	64.0	1.35	0.25	0.02
		Interaction [a]	4.2	268.9	4.21	0.44	0.06

[a] Assumption of sphericity was violated and Greenhouse–Geisser correction was applied.

Similarly, there were no statistically significant differences in OSQ scores among the five SNRs for traffic noise when the noise levels were 55 and 65 dB. However, when the traffic noise level was 75 dB, the OSQ score at an SNR of 6 dB was significantly lower than that at the other SNRs ($p < 0.05$). These results indicate that introducing higher levels of natural sounds than traffic noise might deteriorate the soundscape quality when the traffic noise level is around 75 dB.

Nilsson and Berglund (2006) defined good soundscape quality (GSQ) based on a 5-point scale (“5: Very good”, “4: Good” “3: Neither good, nor bad”, “2: Bad”, and “1: Very bad”) as the proportion of respondents who rated greater than “3: Neither good, nor bad”. On the 11-point scale used in this study, the rating score “5: neutral” can be interpreted as equivalent to “3: Neither good nor bad” on the 5-point scale. Thus, the present study adopted the definition of GSQ as the percentage of the participants who rated greater than “5: neutral” on the 11-point scale.

Figure 6 presents the calculated GSQ of each stimulus as the ordinate against SNRs as the abscissa. The GSQ values are displayed with six sub-datasets depicted by three noise levels (horizontal panels) and two noise types (vertical panels). In the case of traffic noise alone, the mean values of GSQ at a noise level of 55, 65, and 75 dB were 27.9%, 10.4%, and 3.1%, respectively. Overall, the breaker noise was judged to be more annoying than the traffic noise, because the GSQ values from 55 to 75 dB decreased from 8.8% to 0.0% for the breaker noise. This could be attributed to the roughness of the breaker noise with rapid and regular fluctuations, thus causing it to be perceived as more annoying than stationary traffic noise.

Although adding the birdsong or stream sounds enhanced the soundscape quality, the effects gradually decreased as the noise level increased. When the traffic noise level was 55 dB, the mean value of GSQ was approximately 60.0% (SD = 4.7%) across the SNRs, while that for the traffic noise at 65 dB was 35.2% (SD = 4.9%). When the traffic noise was at 75 dB, on average 15.5% of the participants (SD = 3.6%) judged the soundscape quality as good across the SNRs. These results support the findings in previous studies (Hong and Jeon, 2013; Yang and Kang, 2005) that soundscape design using natural sounds is effective in an environment with low or moderate traffic noise levels.

Overall, the effects of the two natural sounds on enhancing soundscape quality for the breaker noise were less significant than the traffic noise. The mean values of GSQ for the breaker noise at levels of 55 and 65 dB were 28.4% (SD = 6.4%) and 22.2% (SD = 4.5%), respectively. Moreover, the mean GSQ value dropped by 8.1% (SD = 2.0 %) at 75 dB.

Regarding the types of natural sounds, significant differences in GSQ between the birdsong and stream sound were not found for the traffic noise at 55 and 65 dB, while the GSQ values with the stream sound were slightly higher than those of the bird song for the traffic noise at 75 dB. In contrast, the stream sound resulted in a further improvement in GSQ values than the birdsong for the breaker noise at 55 and 65 dB, whereas there were no significant differences between the birdsong and stream sounds for the breaker noise at 75 dB across all the SNRs.

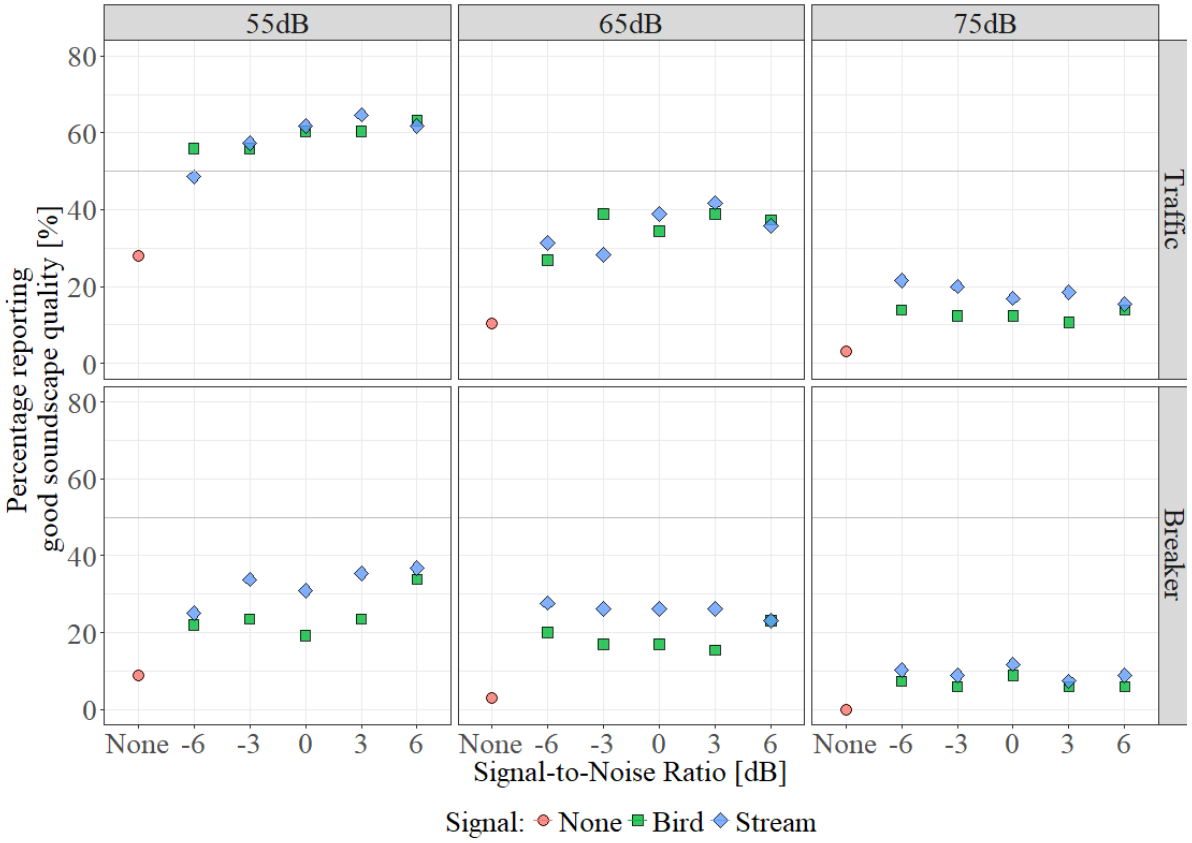


Fig. 6. Percentage of participants reporting good soundscape quality (GSQ). The columns and rows in the faceted plots indicate three different noise levels and two different noise types, respectively.

4. DISCUSSION

4.1. Effect of acoustical characteristics of natural sounds and urban noises on PLN

To explore the critical psychoacoustical characteristics of natural sound and urban noises on PLN, stepwise multiple regression analyses were conducted for the PLN of breaker and traffic noises when adding natural sounds using the four psychoacoustic parameters (*loudness, sharpness, roughness,* and *fluctuation strength*) as independent variables and magnitude estimation value of PLN as a dependent variable.

As summarized in Table 4, *loudness, roughness,* and *fluctuation strength* were selected as the best predictors for the PLN models of both breaker and traffic noises. Both models could explain approximately 99% of variances of the PLN ($p < 0.001$). The *loudness* was the most significant parameter to predict to the PLN of both breaker ($\beta = 0.80$, t = 17.38, $p < 0.001$) and traffic noises ($\beta = 1.22$, t = 60.66, $p < 0.001$).

Interestingly, the *fluctuation strength* and *roughness* values indicating the temporal structure of combined stimuli showed different contributions to the PLN of breaker and traffic noise. Regarding the PLN model for the breaker noise, the standardized regression coefficients of the *roughness* and *fluctuation strength* were 0.18 (t = 10.68, $p < 0.001$) and 0.12 (t = 2.89, $p < 0.001$), respectively. As shown in Fig. 2(f), when the breaker noise was combined with the birdsong, the *roughness* values decreased compared to the breaker noise-alone case. Moreover, adding the birdsong and stream sounds to the breaker noise significantly decreased fluctuation of the breaker noise, as shown in Fig. 2(h). These tendencies demonstrate that both the birdsong and stream used for this investigation could reduce the PLN of the breaker noise.

In contrast, the standardized regression coefficients of the *roughness* ($\beta = -0.17$, t = -10.71, $p < 0.001$) and *fluctuation strength* ($\beta = -0.24$, t = -13.95, $p < 0.001$) had negative contributions to the PLN of the traffic noise, which indicates that the PLN of the traffic noise tended to decrease as the temporal variation of the traffic noise with natural sound increased. Adding the birdsong and stream sounds significantly increased *fluctuation strength* and *roughness* of the combined sounds, as shown in Figs. 2(e) and (g) respectively. These observations support the results of the RM ANOVA tests (Table 2) whereby both the birdsong and stream sound could reduce the PLN of the urban noises.

Table 4. Summary of stepwise multiple regression models of PLN for (a) breaker and (b) traffic noises combined with natural sounds. Standardized regression coefficients for psychoacoustic parameters, *t*-values, and coefficients of determination ($^{*}p < 0.01$, $^{**}p < 0.001$).

Noise	Factors	Standardized Coefficients (β)	*t*	R^2
(a) Breaker	*Loudness*	0.80	17.38^{**}	0.99
	Fluctuation strength	0.18	10.68^{**}	
	Roughness	0.12	2.89^{*}	
(b) Traffic	*Loudness*	1.22	60.66^{**}	0.99
	Fluctuation strength	-0.17	-10.71^{**}	
	Roughness	-0.24	-13.95^{**}	

It is expected from a psychoacoustic perspective that stream sounds might be more effective than birdsong in reducing the perceived loudness of noise, because the spectro-temporal structure of stream sounds is more similar with the noise than birdsong: it is difficult for a birdsong to energetically mask noise due to its high-frequency content and intermittent temporal structure (Axelsson et al., 2010; Nilsson et al., 2014b; Rådsten-Ekman et al., 2013; Rådsten Ekman et al., 2015). The findings of this study, however, show that the PLN reduction effects of birdsong and stream sounds are similar, which demonstrates that a birdsong can also reduce the PLN plausibly due to its saliency by drawing attention away from the noise. However, the PLN reduction effect of the birdsong used for this study stands in contrast to a previous study; Hao et al. (Hao et al., 2016) found that the effect of birdsong in reducing the perceived loudness of soundscape is insignificant. This discrepancy could be caused by the different temporal structure of the traffic noises and different range of SNRs used. Hao et al. (Hao et al., 2016) used passing-by traffic noise with high temporal variability, whereas in this study, traffic noise with low-temporal variability was used because it was recorded from an expressway with constant traffic flow and volume. This corroborates with a previous study (De Coensel et al., 2011) which found that adding birdsong only significantly reduced the perceived loudness of freeway noise (low-temporal variability), and not for traffic noise on major (mid-temporal variability) or minor roads (high-temporal variability).

4.2. Effect of acoustical characteristics of natural sounds and urban noises on OSQ

Similarly, stepwise multiple regression analyses were also performed to develop prediction models for OSQ of the breaker and traffic noises when adding natural sounds using the four psychoacoustic parameters. The results of the multiple stepwise regressions showed that different combinations of psychoacoustic parameters as critical predictors accounting for the OSQ. In the OSQ model of the breaker noise, the *loudness* and *fluctuation strength* were chosen as the best predictors explaining 97% of the variance in OSQ ($p < 0.001$). Meanwhile, the combination of loudness, roughness and sharpness accounted for 96% of the variance in OSQ of the traffic noise ($p < 0.001$).

Table 5 presents the standardized regression coefficients for the individual variables for each model. For both breaker and traffic noise models, the higher *loudness* resulted in the lower OSQ. Interestingly, the *fluctuation strength* had a negative relationship with OSQ for the breaker noise ($\beta = -0.31$, $t = -9.08$, $p < 0.001$). In other words, the OSQ increased as the temporal variation of the combined sounds (the breaker noise with natural sounds) decreased. As shown in Fig. 2(h), adding the stream sound to the breaker noise significantly decreased the *fluctuation strength* of the combined sounds. This demonstrates that using the stream sound could be more effective for the breaker noise to enhance the soundscape quality than the birdsong.

Regarding the traffic noise model, the *sharpness* (β = 0.12, t = 2.95, $p < 0.01$) and the *roughness* (β = 0.16, t = 3.05, $p < 0.01$) had positive relationships with OSQ. As shown in Fig. 2(c), when the traffic noise was combined with the birdsong, the sharpness values of the combined sounds significantly increased. Also, adding the stream sound to the traffic noise resulted in increment of the roughness values of the combined sounds as shown in Fig. 2(e). This implies that both birdsong and stream sounds could contribute to enhance soundscape quality supporting that there was no significant difference in OSQ between the birdsong and stream sounds from the RM ANOVA (see Table 3).

Table 5. Summary of stepwise multiple regression models of OSQ for (a) breaker and (b) traffic noises combined with natural sounds. Standardized regression coefficients for psychoacoustic parameters, *t*-values, and coefficients of determination ($^{*}p < 0.01$, $^{**}p < 0.001$).

Noise	Factors	Standardized Coefficients (β)	*t*	R^2
(a) Breaker	*Loudness*	-0.83	-24.46^{**}	0.97
	Fluctuation strength	-0.31	-9.08^{**}	
(b) Traffic	*Loudness*	-1.08	-21.76^{**}	0.96
	Roughness	0.16	3.05^{*}	
	Sharpness	0.12	2.95^{*}	

These results suggest that the temporal characteristics of the target noises and natural sounds play a critical role in soundscape design approach. Specifically, the findings of this study suggest that increasing the dissimilarity in temporal structure between the target noise and natural sounds might contribute to enhancing soundscape quality. For instance, the stream sound, which has relatively low temporal variance, can reduce the overall temporal variability of the combined breaker and natural sound, thus resulting in a lower amount of attention paid to the breaker noise. This may lead to an improvement in overall soundscape quality. However, a birdsong may not be an appropriate natural sound for a breaker noise because it is intermittent and has a similar temporal variance to the breaker noise. In the case of traffic noise with low temporal variation, the birdsong and stream sound could still attract attention away from the noise, since their temporal variations are relatively larger than the traffic noise.

4.3. Appropriate SNR between natural sounds and noises

This study also uncovered the most appropriate SNR for soundscape design across different noise levels, considering both the reductions in PLN and improvement of GSQ. To achieve this, it is assumed that the optimal ranges of SNR can be determined when the SNRs exhibit a higher reduction in PLN and improvement of soundscape quality. This approach can be quantified by the sum of the reduction ratio of PLN and increment of GSQ across the SNRs, defined as the overall effect of natural sounds (OENS, %). In other words, the OENS value holistically represents the positive effects of natural sounds on the soundscape.

Figure 7 plots the calculated OENS values as a function of SNRs for the three noise levels and two noise types. Only SNRs were considered for the calculation because the effect size of SNR was much larger than that for types of natural sounds. The results showed that the appropriate SNRs were dependent on noise levels and types of noise. For instance, when A-weighted SPL of the traffic and breaker noises were 55 dB, adding the natural sounds had similar effects on OENS across SNRs from −6 to 6 dB. When the A-weighted traffic noise became 65 dB, the OENS increased as the SNR increased and peaked at an SNR of 3 dB, and then slightly fell at an SNR of 6 dB. However, when the traffic noise level rose to an A-weighted SPL of 75 dB, there were negative relationships between SNRs and OENS resulting in the highest OENS at SNR of −6 dB. Meanwhile, for the breaker noise, an SNR of −6 dB was determined as the most desirable when the A-weighted noise levels were 65 and 75 dB.

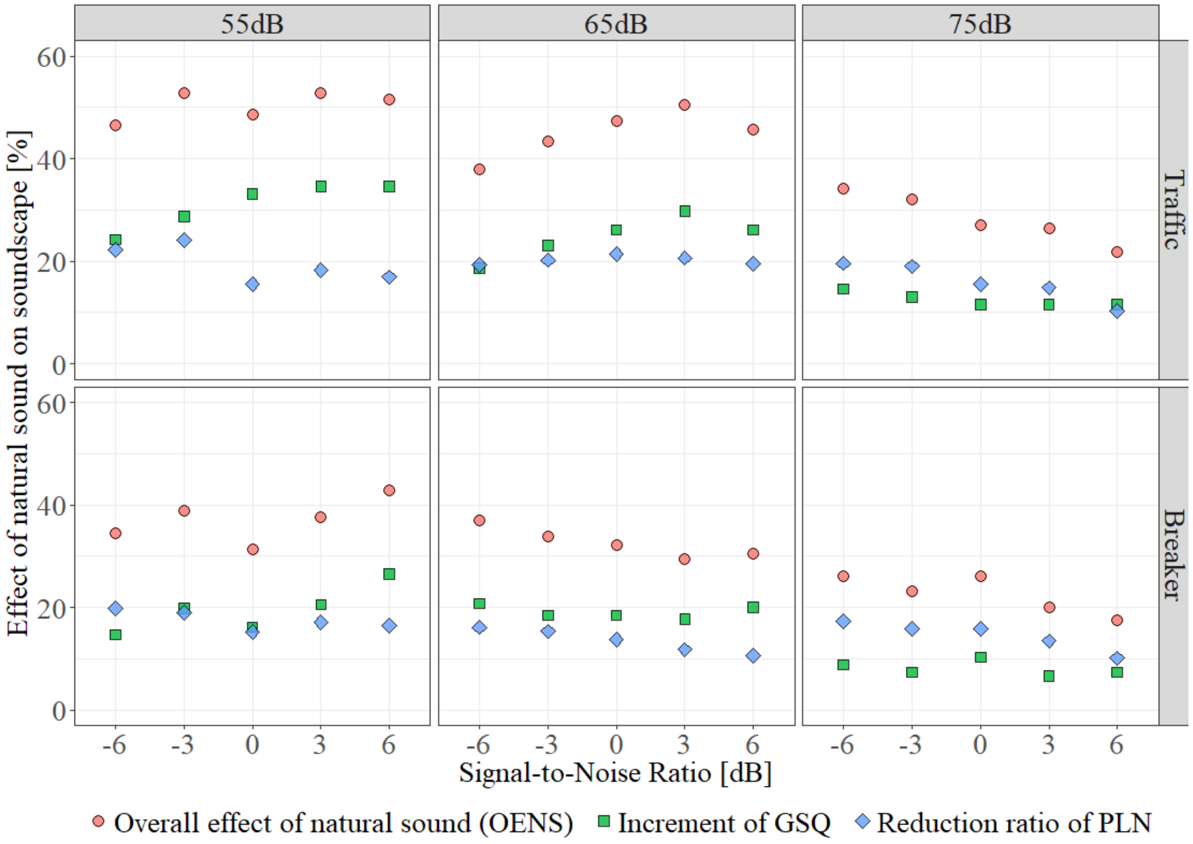


Fig. 7. Effects of natural sounds on soundscape across the SNRs. The columns and rows in the faceted plots indicate three different noise levels and two different noise types, respectively.

4.4. Implications in soundscape design and its limitations

Soundscape intervention by augmentation with pleasant natural sounds can be implemented using two approaches (Kang et al., 2016): by deploying real sound sources (e.g., water fountain) or by installing active sound generating systems (e.g., loudspeakers). For both approaches, the findings of this study can provide useful knowledge for predicting the positive effect of natural sounds. For instance, when deploying a real water fountain in an open space exposed to traffic noise, based on the findings of this study, the appropriate sound levels of the water fountain can be determined by measuring the background noise levels at the given place to optimize the soundscape quality. In addition, when installing loudspeaker systems to transform a place with high noise levels into an acoustically pleasant area, the findings of this study can contribute to the development of a soundscape generating algorithm for the loudspeaker systems, which enables them to generate appropriate types of natural sound at the appropriate levels corresponding to the noise types and background noise levels in the place.

The present study has some potential limitations. Regarding the types of sounds, only two types of urban noise and natural sounds were considered in this study, so studies using noise and natural sound types with a wider range of temporal characteristics are necessary to provide more general conclusions on the effects of natural sounds and urban noises on soundscape perceptions. It should be also noted that the findings in this study cannot be directly attributed to the concept of saliency. Owing to the absence of established objective measures for quantifying the auditory phenomena of saliency, only specific aspects of soundscape perception (i.e., perceived loudness of noise and overall soundscape quality) were subjectively evaluated in this study.

In future studies, computational models of auditory noticeability (saliency) could be employed to quantify noticeability and to explore the relationship between the noticeability of sounds and soundscape perception (Filipan et al., 2019). Moreover, further experimental studies on the impact of noticeability of natural sounds in soundscape design should be performed. For example, the just-noticeable differences of signals mixed with target sounds could be investigated.

Furthermore, a laboratory experiment under controlled conditions may lead to a sterile environment that is limited in reflecting real-world conditions, thus resulting in low ecological validity of the results. For instance, visual factors such as the visibility or mobility of sound sources, overall visual appeal, and congruency between acoustic and visual environments, which may affect soundscape perception, are omitted in this study (Hong and Jeon, 2015, 2014; Joynt and Kang, 2010; Pedersen and Larsman, 2008). Nonetheless, laboratory experiments greatly aid in the investigation of the cause-and-effect relationship between dependent and independent variables by minimizing the effects of extraneous factors.

Mono audio samples were also used in this experiment, thus giving rise to the assumption that the target noise and natural sounds were collocated. Reproductions with such samples are limited in representing the real scenarios because the acoustic environment is experienced in three-dimensional space (Hong et al., 2017a). For instance, the 'masking' efficacy could be dependent on the spatial separation of the target and masker. This dependency is observed in the spatial release from masking (SRM) effect (Ihlefeld and Shinn-Cunningham, 2008; Oberfeld et al., 2012; Srinivasan et al., 2016; Westermann and Buchholz, 2015). Since the SRM effect was derived in a different context, future studies should examine the effect of the spatial separation between target noise and 'masker' on soundscape assessments.

To represent real-life situations and to increase the ecological validity of laboratory studies, virtual reality (VR) technologies have also been increasingly adopted in soundscape studies to create an immersive audio-visual experience (Echevarria Sanchez et al., 2017; Hong et al., 2020, 2019; Maffei et al., 2015; Puyana-Romero et al., 2017). Hence, future studies on the augmentation of urban noises with natural sounds should be conducted using VR systems with spatial audio to provide immersive and realistic experiences.

5. CONCLUSIONS

As acoustic design factors for augmenting natural sounds in soundscape design, the effects of SNRs (–6 to 6 dB), types of noises (breaker and traffic noises), and types of natural sounds (bird and stream sounds) on reducing the PLN and improving the OSQ were explored at three different noise levels (55, 65, and 75 dB) through subjective auditory tests under laboratory conditions. It was found that adding natural sounds to noise could reduce the PLN by approximately 18%.

There were no significant differences in PLN reduction effects between using birdsong and stream sounds, thus supporting the plausibility of saliency in the soundscape approach. It was also shown that adding natural sounds can significantly enhance the overall soundscape quality. Particularly, the natural sounds used were effective when the noise level was lower than 65 dB, whereas the positive effects of the natural sounds decreased as the noise level became higher.

Interestingly, it was found that temporal features of target noise and natural sounds play an important role in soundscape design. For noise with low temporal variability (e.g., stationary traffic or ventilation noise), natural sounds with either high or low temporal variability were effective. However, a natural sound which has low temporal variability could be more appropriate for augmenting non-stationary noise (e.g., a breaker or drilling noise).

Appropriate ranges of SNRs between natural sound and target noise levels were also explored considering both PLN and OSQ. It was found that higher SNRs degraded the effect of natural sounds on improving soundscape with increasing noise levels. Particularly, the most desirable SNR among those tested was −6 dB for both traffic and breaker noises when their A-weighted SPL rose to 75 dB.

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