Effect of perceived dominance and pleasantness on the total noise annoyance responses evoked by augmenting road traffic noise with birdsong/stream sound

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ABSTRACT

Earlier studies suggested that sound preferences or soundscape quality could be improved by augmenting the acoustic environment originally dominated by road traffic noise by birdsong or water sound. However, little has been known on whether and how the total noise annoyance perceptions can also be moderated by augmenting road traffic noise with birdsong/water sound and there is a lack of models that can help portray the noise annoyance response of acoustic environments with traffic sound augmented by birdsong/stream sound. To this end, laboratory hearing experiments were designed to explore the moderating effects of augmenting road traffic noise with birdsong or stream sounds on the total annoyance responses. The responses collected from 94 human participants were employed to construct multivariate models for predicting the probability of evoking a high total noise annoyance response. Results show that multivariate models incorporating perceived level of road traffic dominance and pleasantness of birdsong or stream sound as perceptual factors can better portray the noise annoyance level rated by individuals. The probability of evoking a high total annoyance response tended to be lower when road traffic was not perceived as a dominant sound source, and/or birdsong/stream sound was perceived as pleasant. Of particular contribution of this study is the formulation of a model that can better portray the effects of augmenting road traffic noise with birdsong/stream sound on total noise annoyance responses by including perceived dominance and pleasantness as perceptual factors.

Keywords: Noise annoyance; Soundscape; Birdsong; Water Sounds

1 Introduction

People in an urban environment are often exposed to acoustical environments containing multiple sound sources. Sources may produce unwanted sounds or noises (e.g. road traffic noise, human sounds) and/or wanted sounds (e.g. natural sounds including water sound and birdsong). In the past and even now, extensive efforts have been placed on understanding the annoyance responses induced by a single unwanted noise source, e.g. road traffic or aircraft noise. However, multiple sound sources may evoke quite different noise annoyance responses from those evoked by a single sound source. Thus, studies have been devoted to understanding the annoyance response due to the combination of two sound sources.

For the acoustic environment containing a combination of unwanted sounds, major focuses of previous studies have been placed on revealing the total annoyance responses due to two noise sources, mostly from two transportation sources, e.g. road traffic and railway. Kim et al. (2019) reported that simultaneous exposure to two noise sources (e.g. road traffic and railway) may evoke more extensive reactions than exposure to a single noise source at the same sound pressure level. Other contrary evidence suggested that some noise sources might have an inhibiting effect on the other noise source. For example, the noise annoyance responses to industrial noises with a main spectral component at 100 Hz was found to be lower when there was a background noise (Alayrac and Marquis-Favre, 2011).

In the meantime, a number of empirical models have been developed to predict the effect of exposure to a combination of unwanted sounds (Pierrette et al., 2012; Marquis-Favre et al., 2021). Many earlier models embraced physical factors, which are factors that can directly describe the acoustic environment objectively, as predictors of total annoyance responses to the exposure of a combination of sound sources. This type of models is referred as physical models (Aumond et al., 2017). Factors such as types of sounds, sound levels of individual sources, and differences in sound level between two sources (i.e. often expressed in terms of signal-to-noise ratio) are examples of physical factors adopted in physical models. Physical models have been formulated based on an underlying assumption that the total annoyance response due to exposure to a combination of sounds can be expressed as a function of sound levels of individual sources, e.g. combined aircraft and traffic noise exposure (Nguyen et al., 2012) and combined railway-traffic noise (Lechner et al., 2020). Specifically, the energy difference models postulate that total annoyance responses are determined by the total sound level of the combined noise source and the difference in sound levels of individual noise sources. This model has been applied for predicting the total annoyance responses to exposure of a combination of industrial noise exposure (Morel et al., 2012).

On the other hand, perceptual models (Aumond et al., 2017) have also been formulated to link the total annoyance responses with perceptual factors, which are associated with the perception of the acoustic environment. Classical perceptual models mainly include annoyance ratings of individual sound sources as independent variables. The linear model with the annoyance ratings of individual sound sources attempted to differentiate between the sources by describing the global annoyance as a weighted sum (Botteldooren et al., 2002). Dominance model, or the strongest component model, assumes that the total annoyance from a combination of sound sources is equivalent to the annoyance from a single dominant source (Berglund et al., 1981). Dominance model was shown to be the most useful model for predicting the total annoyance responses in the vicinity of those airports in Vietnam where road traffic noise was more dominant than aircraft noise (Nguyen et al., 2012).

In addition, studies have also attempted to include personal trait characteristics in models depicting annoyance responses of combined sound exposures (Frescura and Lee, 2021). In particular, individual noise sensitivity has been confirmed to be an important factor for the total annoyance responses in a combined acoustic environment (Wothge et al., 2017).

Hitherto, little advances have been made to include perceptual factors other than annoyance resulting from individual sound sources together with physical factors for predicting the total annoyance responses of combined sound sources. Majority of the foregoing models are only applicable for portraying acoustic environments containing two unwanted sound sources, but not cater for portraying acoustic environment embracing an unwanted sound and a wanted sound, e.g. natural sound. However, there have been observations showing that total noise annoyance responses would be moderated in case the sound source added to the acoustic environment was a wanted and/or pleasant sound, e.g. a natural sound. For example, augmenting the acoustic environment with road traffic noises by water sound or birdsong has often been shown to be able to reduce loudness and thus annoyance induced by road traffic noises (Jeon et al., 2010; Hao et al., 2016).

Even for the same types of wanted sounds, the heterogeneity of sounds may evoke different sound perceptions even from same individuals. For example, birdsong with high frequency content tended to be more preferable and have a stronger capability to increase the pleasantness and preference. On the contrary, low-frequency birdsong has been perceived as a negative source signal as they evoke aggressive behaviors (Hedblom et.,al 2014). The nearly pure-tone high-frequency sounds of corvids also connote a sense of fear (Morton, 1997). For water sound, previous studies suggested that natural stream or sea wave sounds tended to be more pleasant than waterfall sounds (Galbrun and Calarco, 2014).

In addition to the observations that perceived sound dominance is considered a critical factor for distinguishing major types of total annoyance responses in many perceptual models, many recent soundscape studies also suggested that perception of dominant sounds was one of the important factors for soundscape quality in the presence of a combination of wanted and unwanted sound sources (Perez-Martinez et al., 2018). Regardless of the complexity of sound sources comprising a given acoustic environment, soundscape quality is driven primarily by perceived dominant sounds, e.g. the most prominent positive effects were produced by natural sounds, and the most adverse effects were driven by construction and traffic sounds (Liu, Yang, Xiong, & Yang, 2019; Perez-Martinez et al., 2018; Ren et al., 2018; Ren et al., 2022). Higher acoustic comfort evaluation ratings would be obtained if the first dominant sound type moved from mechanical, anthropogenic to nature-related (Ren, 2023). As annoyance is one of the eight major components of soundscape quality (i.e. Eventful, Uneventful, Vibrant, Monotonous, Clam, Chaotic, Pleasant and Annoying) (ISO, 2014), it is hypothesized that the total annoyance responses are also influenced by the subjective perception of dominant sounds.

Besides, it is unclear whether perceived dominance and/or pleasantness of the natural sound augmenting the acoustic environment vary with the relative contribution of sound sources within the acoustic environment. There is also a lack of understanding on whether and how the perceived dominance and pleasantness of the natural sound augmenting the acoustic environment perceived by people affect the total annoyance responses even though birdsong or water sound could improve soundscape perception (Brungart, 2001; Hong et al., 2020), and perceived dominance and pleasantness were shown to be important factors for good soundscape quality (Pérez-Martínez et al., 2018). Moreover, there has been no openly reported model that can help predict the total annoyance responses by embracing both physical factors, and perceived dominance and pleasantness of a natural sound in an acoustic environment with a combination of wanted and unwanted sounds. Accordingly, there are three major objectives of this study. First, this study aims to investigate whether perceived dominance of the natural sound varies with the relative contribution of natural sound and the road traffic noise levels. Both birdsong and stream sound have been employed as exemplary of natural sounds. Second, it aims to formulate multivariate models by including perceptual factors like perceived dominance and pleasantness of a natural sound together with physical factors to help predict the effects of exposure to different combinations of natural sound and road traffic sound on the total noise annoyance responses. Third, with the formulated model, it aims to investigate how the noise annoyance moderation effects of stream sound/birdsong vary with the level of dominance and pleasantness being perceived by people. Of particular contribution of this study is to acquire better understanding of the effects of perceived dominance and pleasantness of birdsong/stream sound in augmenting road traffic noise on total noise annoyance responses.

2 Methodology

A set of laboratory experiments was carried out to investigate the effect of augmenting road traffic noises by stream sound or birdsong on total noise annoyance responses. The experiments were designed with the ultimate aims to use the collected annoyance responses for constructing multivariate models that can evaluate and quantify the effects on the total annoyance responses by augmenting acoustic environment with road traffic sound by birdsong or stream sound. In addition, the responses have also been used for investigating the relationships between perceived levels of dominance and the relative contribution of individual sounds.

2.1 Audio stimuli

Three different sound sources were investigated in this study. They were stream sound, birdsong, and road traffic sound. The birdsong clip was excerpted from a recording featuring multiple bird species chirping during dawn chorus in the woodlands. The recording was purchased from a professional sound effect website (available at http://www.prosoundeffects.com). Stream sound and road traffic sound were extracted from half-an-hour binaural records of a quiet park and a busy trunk road. The extracted sounds were manually checked to ensure that no other disturbing sounds were present. Besides, the traffic sound extracted was continuous road traffic sound. The *SPL*s were calibrated using B&K 4128C (Head and Torso Simulator) and B&K 2144.

Road traffic sound was mixed with birdsong /stream sound to create a 30s sound clip with the aid of B&K 4128C, B&K 2144 and the software Audacity. Sound clips of the road traffic noise were played by using the SENNHEISER HD 280 pro headphones mounted on the B&K 4128C. The SPL of the clips played by the headphones were analysed by the B&K 2144 connected to the B&K 4128C. Audacity was used to adjust the sound level of the sound clips until the required SPL were achieved. The master volume of the computer playing the clips, which would also be used during the experiment, was kept unchanged during the process to ensure that the set SPLs of the sound clips played would not be changed during the experiment. Similarly, the SPLs of the stream/birdsong clips were also adjusted in the same manner. The traffic sound and stream/birdsong clips with the required SPLs were then mixed by using Audacity. In the experiments, the sound levels of road traffic were set to 55, 60, or 65 dBA. The differences in *SPL*s between stream/birdsong and road traffic sound (which is referred as “Signal-to-Noise ratio for stream sound” “*SSNR*” and “Signal-to-Noise ratio for birdsong” “*BSNR*” in this study) ranged from -9 dB to +9 dB, in a step of 3 dB. A negative *SSNR* or *BSNR* value indicates that the *SPL* of road traffic sound is higher than that of the birdsong or stream sound, and vice versa. In total, there were 3x7x2=42 mixed sound clips.

2.2 Experimental setups

A two-part laboratory experiment was performed in a study room in the Department of Building Environment and Energy Engineering of the Hong Kong Polytechnic University. The background noise level of the test room was measured to be 45 dBA approximately. Ethical appropriateness involving human subjects has been reviewed and approved by the Hong Kong Polytechnic University. Participants were asked to sign a consent form to participate in the experiment before it started. They were also acknowledged that they could withdraw at any time during the experiment. In the experiment, a series of audio stimuli were presented to participants through SENNHEISER HD 280 pro headphones. Originally, participants were required to listen to 51 sound clips (including 9 single sound clips and 42 mixed sound clips). To mitigate the chance of degradation in the response quality, the mixed sound clips were divided into three groups and the experiments were arranged in two parts so that each participant was only required to listen to 9 single sound clips (Part A) and 14 mixed sound clips (Part B). It took about 15 minutes for a participant to complete the whole experiment.

Part A examined the overall sound pressure levels (*SPL*s) at which participants perceived traffic sound, stream sound and birdsong as annoyed or pleasant. Participants were required to listen to 9 single sound clips (i.e., 3 stream sound clips, 3 birdsong clips, and 3 traffic noise clips) in which the total *SPL*s were set to 55, 60 and 65 dBA, respectively. These clips were arranged in a random order and the order was the same for each participant. Each clip was played for 30 seconds and a 10-second break was allowed between two consecutive clips. Participants were asked to rate the pleasantness for the stimulus in each clip on a questionnaire using an 11-point scale (where '-5' denotes '*Extremely annoyed*', '0' denotes '*Neutral*', and '5' denotes '*Extremely pleasant*') (See Fig. 1).

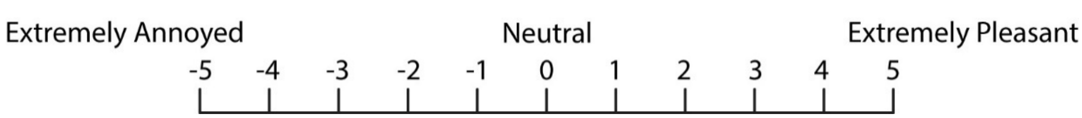


Fig. 1 Labels presented to participants to elicit the annoyance / pleasantness rating of the single sound clips

In Part B, participants were asked to compare the effect of adding stream sound and birdsong to road traffic sound respectively on the total noise annoyance responses. 42 mixed sound clips were divided into 3 fixed groups of 14 clips in a random manner. Each participant was only required to listen to one group of the sound clips. These groups of sound clips were assigned to the participants in the sense that Set A, B and C were assigned to the first, second and third participants. Set A would then be assigned to the fourth participant and so forth. Similar to Part A, each clip was played for 30 seconds and a 10-second break was allowed between two consecutive clips. Participants were asked to give a noise annoyance rating to each sound clip using an 11-point scale (where '0' denotes "*Not annoyed at all*", '5' denotes '*Neutral*', and "10" denotes "*Extremely annoyed*") (See Fig. 2). In addition, they were asked to identify the type of sound source they perceived to be dominant and assign the levels of dominance in each of the sound clips containing mixed sound sources with an 11-point scale (where "-5" is "*Traffic sound dominant*"; "0" is "*Neutral*; "5" is "*Natural sound dominant*").

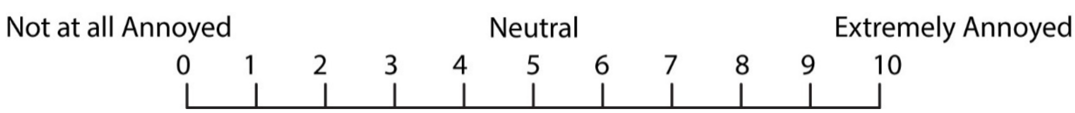


Fig. 2 Labels presented to participants to elicit the annoyance rating of the mixed sound clips

At the end of the experiments, each participant was requested to provide personal information including gender, age, self-assessed health status and noise sensitivity. "Noise Exposure", which refers to the specific type of noise source the participants were usually exposed to in their homes, were asked.

2.3 Formulation of multivariate models for predicting high total annoyance responses

Logit models have been formulated to estimate the likelihood of evoking a high total annoyance response when the acoustic environment with road traffic noise was augmented by birdsong and stream sound respectively. Logistic regression is a form of regression model that can be used to handle the case involving a dichotomous dependent variable. To facilitate the logistic analysis for estimating the probability of occurrence of evoking a high annoyance response, the annoyance ratings were regrouped into two categories i.e. y = 0, for the original annoyance rating ≤ 7 (i.e. low and moderate annoyance response); y = 1 for the original annoyance rating > 7 (i.e. high annoyance response).

Specifically, a logit function can be formulated from the collected responses and used to predict the probability of evoking a high annoyance response:

$$P(High\ Annoyance\ response = y) = \frac{\exp(Z)}{1+\exp(Z)} \quad \text{(Eqn 1)}$$

where Z is a latent variable, which is assumed to be a linear additive function of the independent variables x_i:

$$Z = \sum \beta_i x_i + \varepsilon \quad \text{(Eqn 2)}$$

where β_i is the regression coefficient pertaining to x_i. The direction of an effect can be visibly interpreted from the sign of the estimated regression coefficient in the logit function:

a negative sign indicates that the likelihood of evoking a high annoyance response decreases as the value of the independent variable increases, and vice versa.

Meanwhile, the goodness-of-fit of the model can be measured by the McFadden ρ^2 (McFadden, 1973). It is one of the most popular Pseudo R^2 measures for logistic regression (Veall and Zimmermann, 1996) and analogous to *R*-squared commonly applied in linear regression in that the log likelihood of the intercept model can be regarded as the total sum of squares while the log likelihood of the full model can be regarded as the sum of square errors. Usually, a model with McFadden ρ^2 value higher than 0.2 is considered acceptable (Zhou et al., 2018).

3 Results and Data Analysis

Full-scale experiments were successfully performed with 94 participants. Each participant received a HK$50 (~US$6.5) supermarket cash coupon as a reward upon successful completion of the experiments. 84 participants were full-time students recruited from the University. An overwhelming majority of the participants rated themselves as normal, sensitive or very sensitive to noise (89.4%) and of normal health, healthy or very healthy (86.3%). Table 1 summarizes the personal characteristics of all the survey participants.

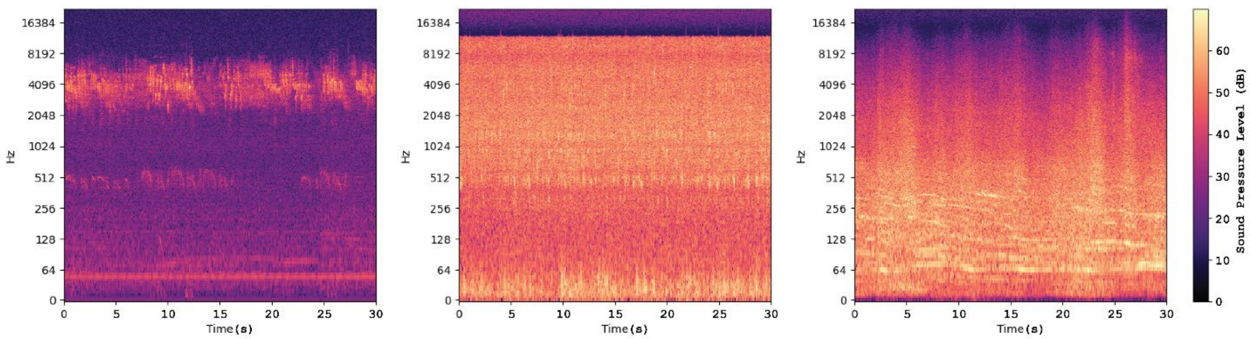
Table 1 The profile of personal characteristics of the participants

Item Description		No. of participants	Percentage of total number of participants	Mean (Standard deviation)
Gender	Male	22	23.4%	--
	Female	72	76.6%	

Age	18-20	15	16.0%	22.15 (5.47)
	20-25	67	71.3%	
	26-30	4	4.2%	
	>30	8	8.5%	
Self-reported Health status	Very unhealthy	0	0%	3.44 (0.77)
	Unhealthy	13	13.7%	
	Normal	30	32.0%	
	Healthy	48	51.1%	
	Very healthy	3	3.2%	
Self-reported Noise sensitivity	Not at all sensitive	0	0%	3.68 (0.85)
	Not sensitive	10	10.6%	
	Normal	23	24.5%	
	Sensitive	48	51.1%	
	Very sensitive	13	13.8%	
Noise exposure	Highway	7	7.5%	--
	Busy traffic road	47	50.0%	
	Lane	33	35.1%	
	Others	7	7.4%	

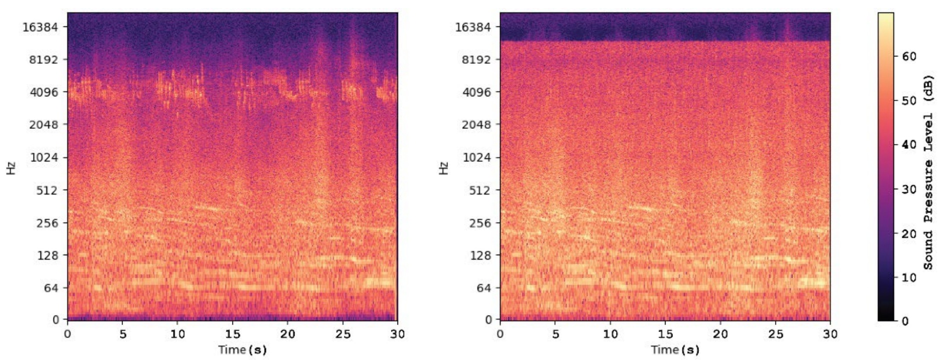
2.3 Sound spectral analysis

The spectral distribution profiles of different types of sounds and their combinations were analyzed. Fig. 3 to 6 show the spectrogram and spectra of road traffic sound, birdsong, stream sound, and their mixed sounds at 60 dBA, respectively.



(a) (b) (c)

Fig. 3 Spectrogram of (a) birdsong, (b) stream sound and (c) traffic sound at 60dBA



(a) (b)

Fig. 4 Spectrogram of (a) traffic-birdsong, (b) traffic-stream sound when the sound levels of both natural sound and traffic sound were at 60 dBA

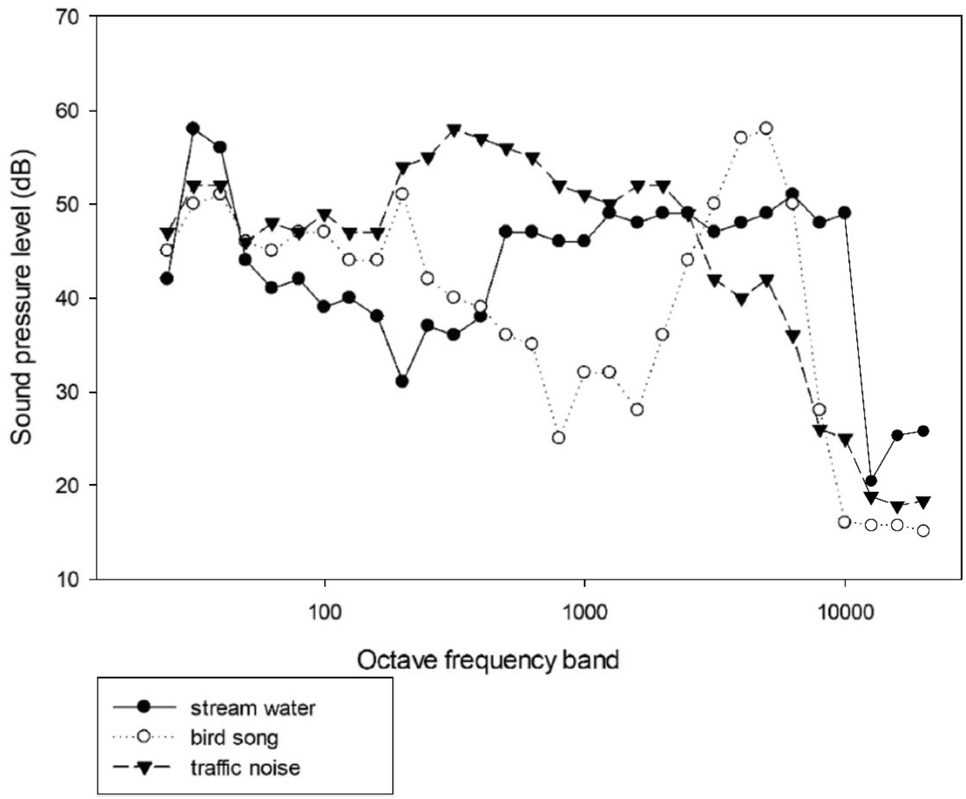
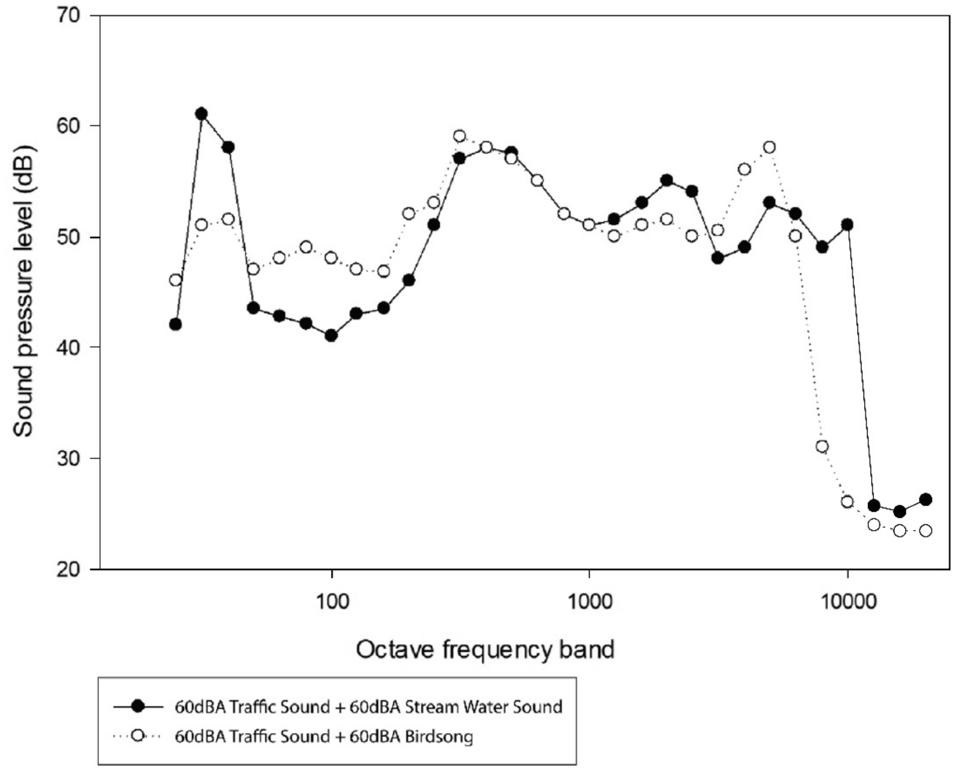


Fig. 5 The sound spectrum of single sound at 60 dBA



Notes:

- Solid line denotes that the sound stimuli were produced by mixing stream water sound at 60dBA with road traffic sound at 60 dBA.
- Dotted line denotes that the sound stimuli were produced by mixing birdsong at 60 dBA with road traffic sound at 60 dBA.

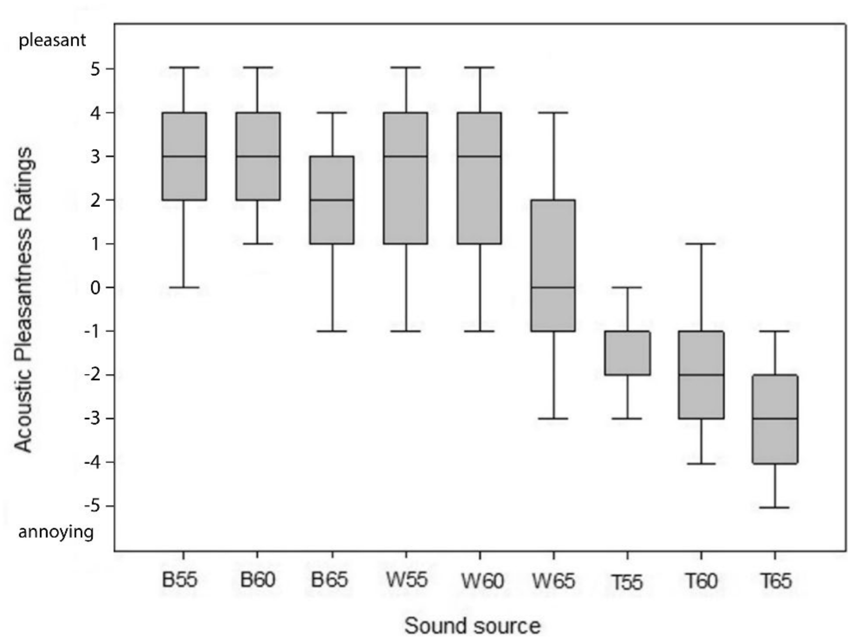
Fig. 6 The sound spectrum of mixed sounds

Upon closer examination of the sound spectra, road traffic sound had a relatively higher sound pressure level at low frequency levels ranging from 80 to 2000Hz. Sound pressure level of road traffic sound sank at high frequency levels. Stream sound had higher sound pressure level at high frequency levels between 500 and 10000 Hz. The sound pressure levels of the stream sound were generally higher than those of road traffic sound when the frequency level was above 2000 Hz. In comparison, the sound pressure level of birdsong fluctuated more widely when compared to stream sound or road traffic sound. The sound pressure levels of all the three sounds were relatively low beyond 10000 Hz.

The spectra were found to be different after the acoustic environment with road traffic sound had been augmented with birdsong or stream sound. However, the sound pressure levels of the combined sounds remained more or less constant at different frequency levels. The spectral characteristics of the two combined sounds shown in Fig. 2 were similar for the same natural sound and road traffic sound. However, the sound pressure levels of the combination of birdsong and road traffic sound at frequency levels ranging from 60 to 1000 Hz were still slightly higher. Besides, sound pressure levels traffic-birdsong and traffic-stream sound were low beyond 10000 Hz. When comparing among the sound spectra of 5 single and mixed sound clips, the spectra of combined sounds were observed to be relatively flatter than those of single sound sources.

2.4 Pleasantness ratings for individual sound sources

Fig. 7 shows the pleasantness ratings assigned by the participants when exposed to birdsong or stream sound, and road traffic sound at 55, 60 and 65 dBA, respectively. A series of t-test was also performed to investigate whether mean pleasantness ratings of two sounds were different, or whether they were different from 0 ("0" means the sound was neither pleasant nor unpleasant). On average, birdsong was perceived to be pleasant, while road traffic sound was perceived as annoying for all the three studied sound levels ($p<0.0001$ for both sounds at all three sound levels). In contrast, stream sound was perceived to be pleasant at 55 and 60 dBA ($p<0.0001$ for both sound levels) but was perceived to be neither pleasant nor annoying at 65 dBA (p=0.1642). Although birdsong was perceived to be more pleasant than stream sound at 60 (p=0.0037) and 65 dBA (p<0.0001), birdsong and stream sound were perceived to be equally pleasant at 55 dBA (p=0.7618).



Notes:

- '-5' denotes 'Extremely *Annoying*', '0' denotes '*Neutral' and* '5' denotes 'Extremely *Pleasant*'
- *B – birdsong, W - stream sound, T – road traffic sound*
- *The middle bars of the box plots represent the mean values of pleasantness.*

Fig. 7 Acoustic pleasantness ratings for different types of sounds at different sound levels

2.5 Perceived sound dominance and total noise annoyance responses

Fig. 8 shows the percentages of participants not perceiving road traffic as a dominant sound source (i.e. dominance rating > -3) in an acoustic environment containing both road traffic sound and birdsong. It can be observed that the percentage of participants not perceiving road traffic as a dominant source was higher as the *SPL* of birdsong increased. Also, it was observed that the size of increment in percentage became larger at higher road traffic sound levels. Fig. 9 shows that similar phenomena occurred for stream sound with regard to changes in *WSNR* and road traffic sound levels. However, the rate of change in percentage of the participants not perceiving road traffic as a dominant sound source against *SNR* tended to be higher for birdsong than stream sound at higher road traffic sound levels.

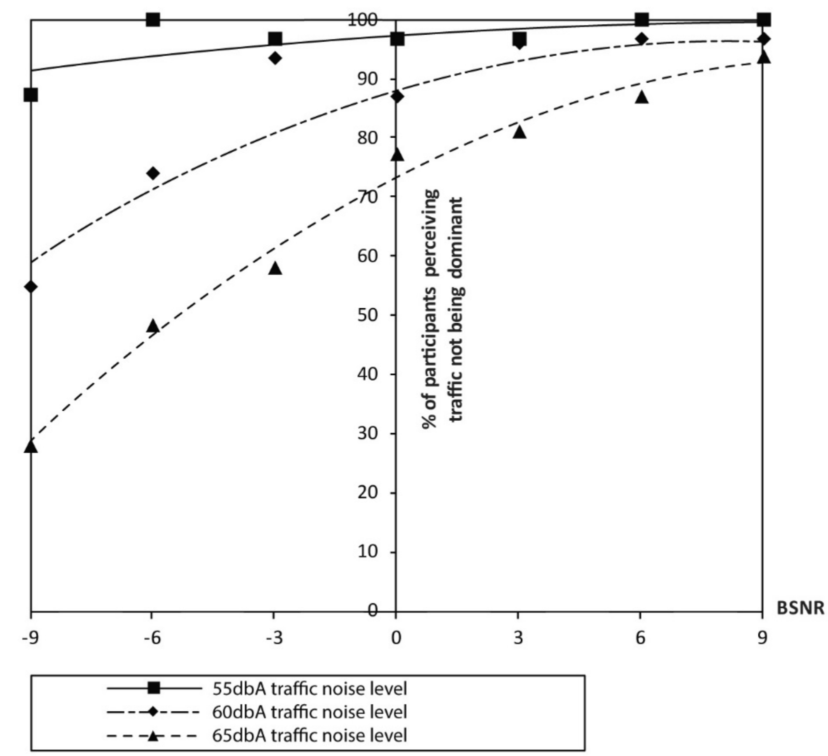


Fig. 8 Percentages of participants not perceiving road traffic as a dominant sound source in an acoustic environment containing both birdsong and road traffic sound at different *SNR*s

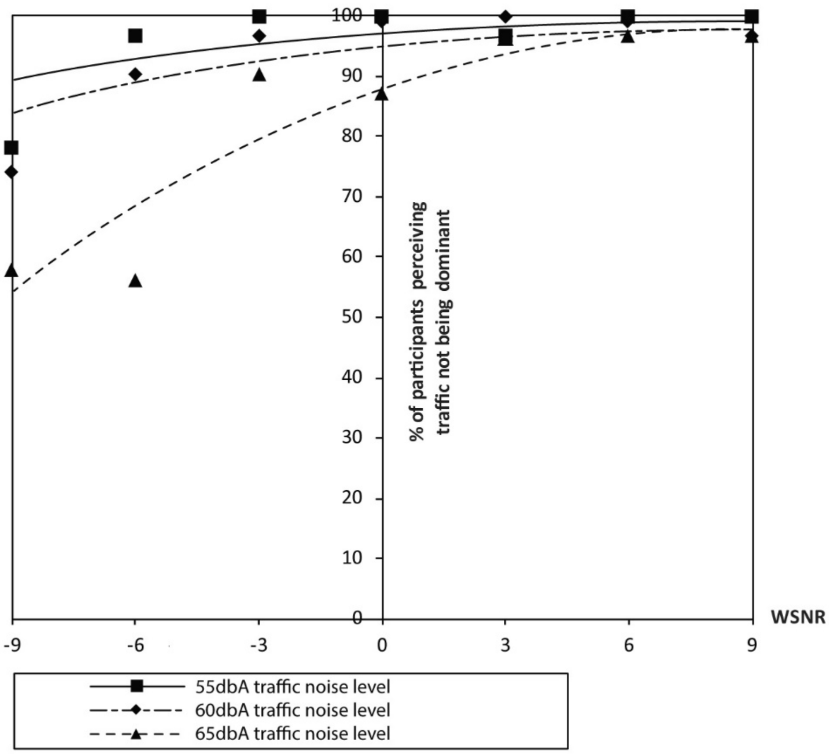


Fig. 9 Percentages of participants not perceiving road traffic as a dominant sound source in an acoustic environment containing both road traffic and stream sounds at different *SNR*s

2.6 Multivariate models for predicting high total annoyance responses

In order to deal with the possible issue of multicollinearity of the independent variables, the models were formulated in a stepwise manner. An independent variable would only be included if they can significantly improve the model's goodness-of-fit without compromising the significance of other explanatory variables when formulating the multivariate models for predicting high total annoyance responses. Besides the variables associated with the acoustic environment, some variables associated with personal characteristics have also been included in the models. The variables gender, age, self-rated health status, and noise exposure have not been included in the models as they exerted no significant influences on the total annoyance responses. Moreover, the Variance of Inflation Factor (VIF) would also be computed after the formulation of the model. Logistic regression models would not be considered to be suffering from the problem of multicollinearity if the VIF values of the independent variables were smaller than 2.5 (Midi et al., 2010). Table 2 lists the descriptions of all the variables in the models.

Table 2 Descriptions of the variables in the ordered logit models

Variables	Description	Unit
TRAFFIC	*SPL* of Road traffic sound	dBA
BSNR/WSNR	Signal-to-noise ratio of birdsong/stream sound	dB
DOM	Perceived sound dominance rating for a mixed sound clip assigned by participants, where dominance rating ≤ -3 was recoded as “0” (perceiving road traffic as a dominant sound source), and rating > -3 was recoded as “1” (not perceiving road traffic as a dominant source)	-
PLBird	Pleasantness rating of birdsong at 65 dBA, where pleasantness rating ≤ 0 (not pleasant) are recorded as “0”, and rating > 0 was recoded as “1” (pleasant)	-
PLStream	Pleasantness rating of stream sound at 65 dBA, where pleasantness rating ≤ 0 (not pleasant) was recorded as “0”, and pleasantness rating > 0 was recoded as “1” (pleasant)	-
SEN	Self-rated noise sensitivity status, where moderate and low sensitivity (original rating ≤ 3) is recoded as “0”, and high sensitivity recoded as “1” (original rating > 3)	-

Statistical package STATA was used to perform the regression analysis. As it is also of paramount interest to understand if the inclusion of both physical and perceptual factors will give better models than physical models, the McFadden's ρ^2 of the models including physical factors only and both physical and perceptual (i.e. perceived dominance and pleasantness) factors with noise sensitivity have been compared. It was found that the McFadden ρ^2 values of the models for birdsong and stream sound increased from 0.233 to 0.253 (which is analogous to r^2 from 0.516 to 0.566) and 0.249 to 0.304 (which is analogous to r^2 from 0.548 to 0.649) respectively after including the perceptual factors as independent variables. Likelihood ratio Chi-square test also showed that the models including perceptual factors as independent variables were significantly different from the models without these factors ($p < 0.0001$ for both birdsong and stream sound models). The inclusion of both physical and perceptual factors has significantly improved the goodness-of-fit of the models. Table 3 and 4 show the results of logistic regression.

Table 3 Logistic regression results of birdsong

Independent Variable	Coefficient Estimate	Significance Level	VIF
TRAFFIC	0.3276	<0.001**	1.14
BSNR	0.0472	0.024*	1.14
DOM	-0.8085	0.004**	1.27
PLBird	-0.8085	0.002**	1.00
SEN	-20.0381	<0.001**	1.00

* Significant at 0.05 level; **Significant at 0.01 level

Table 4 Logistic regression results of water stream sound

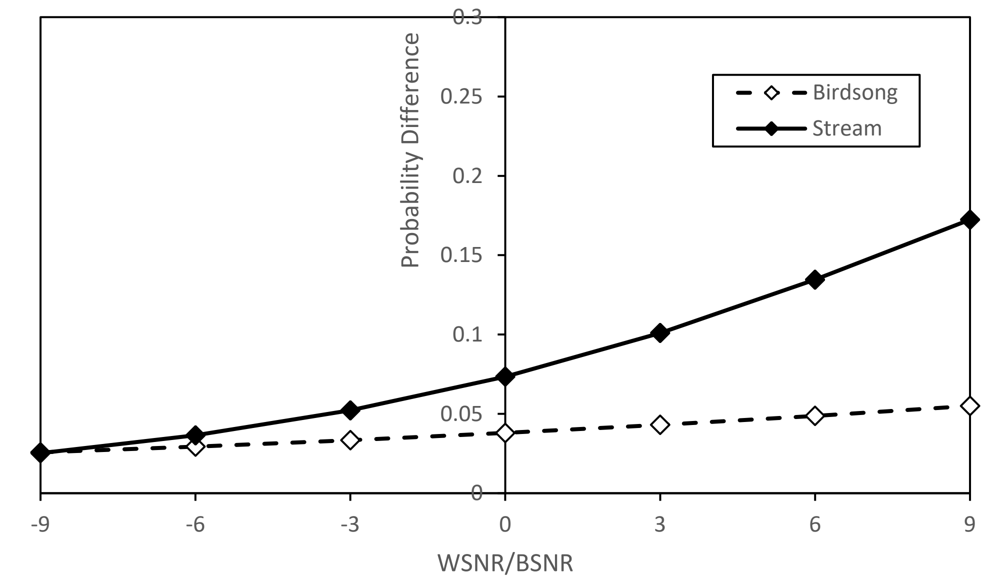
Independent Variable	Coefficient Estimate	Significance Level	VIF
TRAFFIC	0.3144	<0.001**	1.04
WSNR	0.1315	<0.001**	1.11
DOM	-1.0645	0.004**	1.15
PLStream	-1.3021	<0.001**	1.00
SEN	-18.8531	<0.001**	1.01

* Significant at 0.05 level; **Significant at 0.01 level

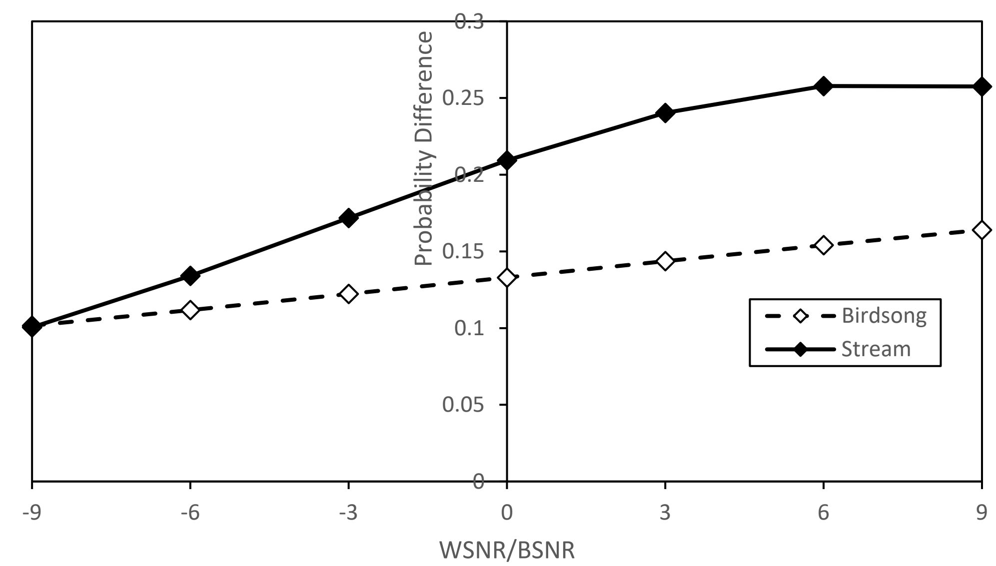
It can be seen from Tables 3 and 4 that the VIF values of all the independent variables were smaller than 2, meaning that multicollinearity should not be an issue of the models. *SPL* of road traffic, perceived dominance by road traffic sound, *SPL* of birdsong/stream sound, pleasantness of birdsong or stream sound at 65 dBA, and an individual's self-rated noise sensitivity status were statistically significant predictors of a high noise annoyance response. Augmenting the acoustic environment with road traffic sound by using birdsong or stream sound would be less likely to evoke a high annoyance response (i.e. likelihood). Besides, an individual's self-reported noise sensitivity status was also found to influence the likelihood. A high noise sensitive individual, inter alia, would have a higher likelihood of evoking a high noise response, which is in line with earlier findings obtained from similar nature and thus can act as a proof of construct validity.

Noticeably, the dominance of road traffic sound and pleasantness of the natural sound perceived by an individual were also found to play important roles on the likelihood of evoking a high annoyance response.

As shown in Fig. 10, for scenarios involving birdsong or stream sound, the values of probability difference (i.e. probability of evoking high annoyance response when DOM equaled 0 – probability of evoking high annoyance response when DOM equaled 1) were always higher than 0. This means that lower likelihood would be resulted if an individual did not perceive road traffic as a dominant sound source. Similar observations were observed when road traffic sound level was at 55, 60 or 65 dBA. Meanwhile, the probability difference was also affected by the SNR. When *SPL* of road traffic equaled 55 or 60 dBA, the probability difference basically increased with *SNR*. However, a different trend can be observed when road traffic equaled 65 dBA. For acoustic environment augmented by stream sound, the probability difference increased when SNR was between -9 and -3 dB, and then decreased afterwards. On the other hand, the probability difference gradually decreased when SNR increased for acoustic environment augmented by birdsong.


Probability Difference
0.3
0.25
0.2
0.15
0.1
0.05
0
-9
-6
-3
0
3
6
9
WSNR/BSNR
Birdsong
Stream

(a)


Probability Difference
0.3
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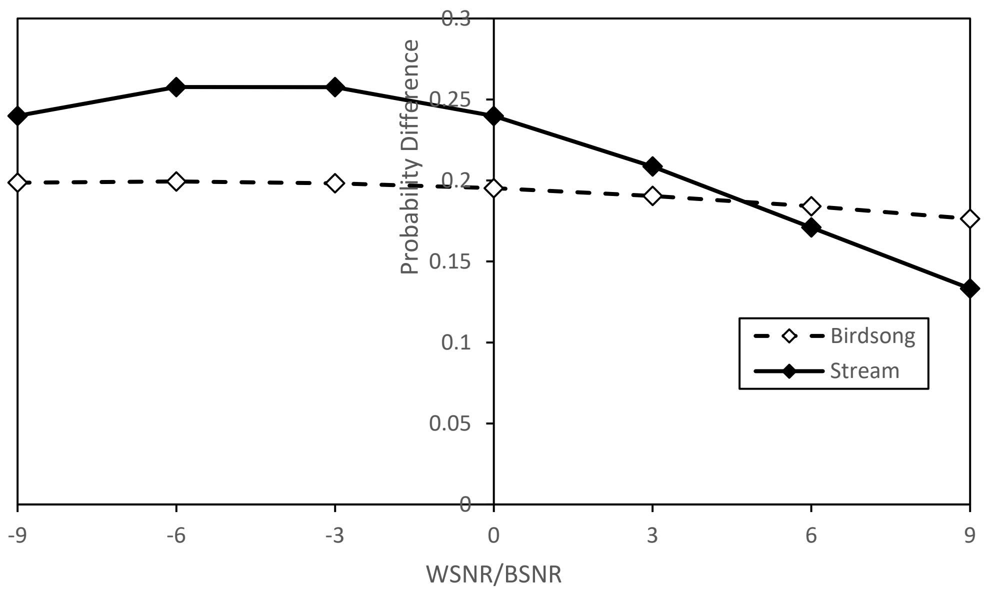
WSNR/BSNR
Birdsong
Stream

(b)

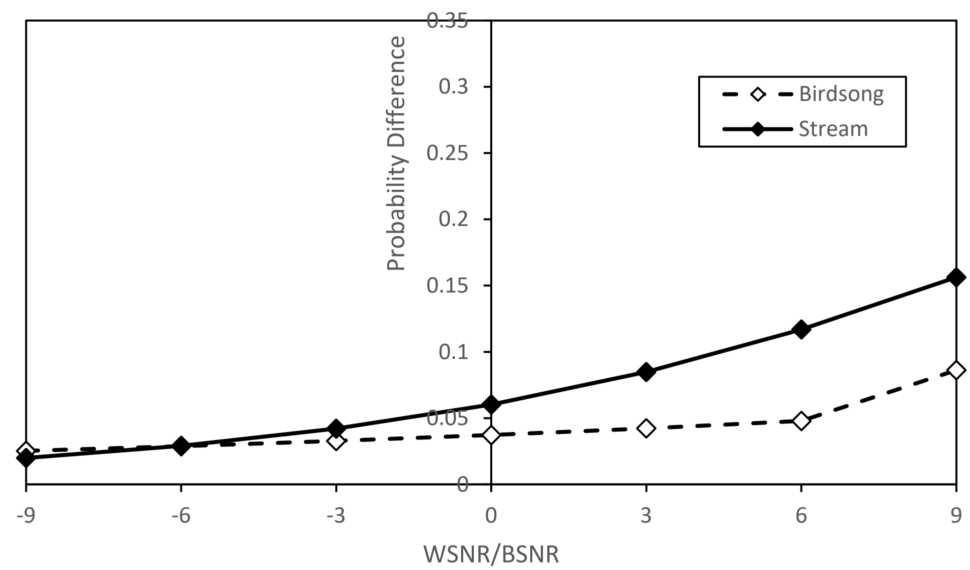


(c)

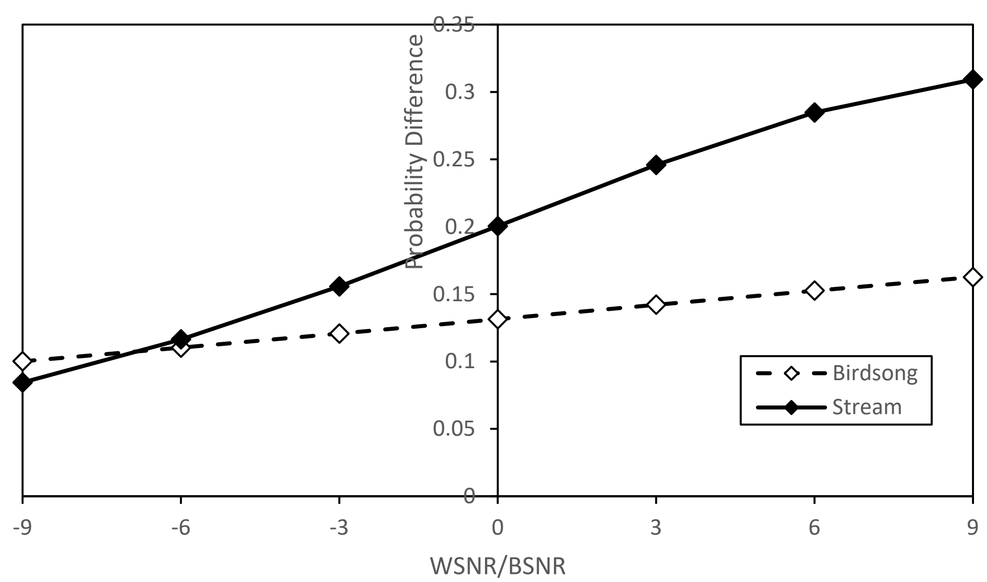
**Probability Difference = Probability of evoking a high annoyance response when DOM equals 0 - Probability of evoking a high annoyance response when DOM equals 1*

Fig. 10 The difference in the probability of evoking a high annoyance response for sound environments augmented by birdsong or stream sound between different perceived levels of road traffic sound dominance when the road traffic noise level was at (a) 55dBA, (b) 60dBA and (c) 65dBA

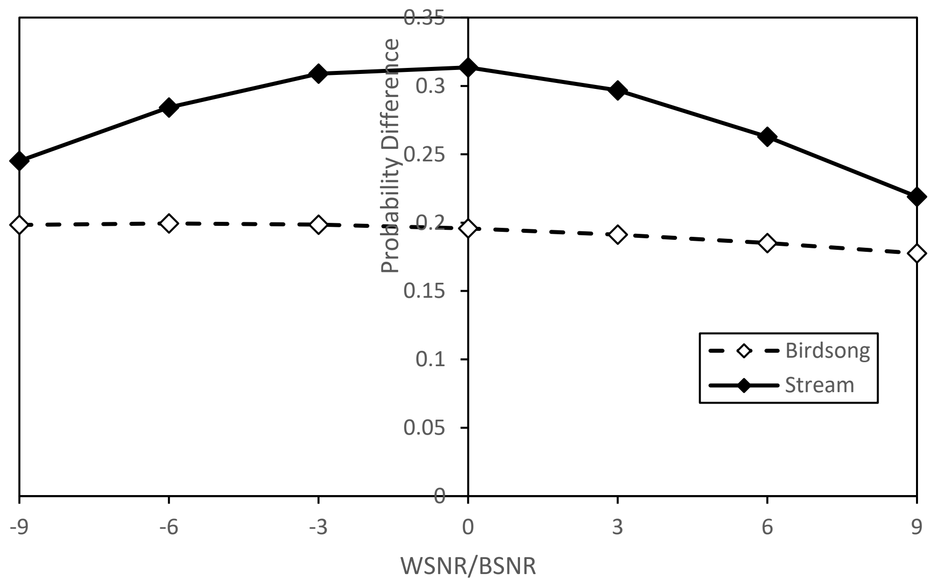
Fig. 11 shows the probability difference (probability of evoking high annoyance response when pleasantness level equaled 0 – probability of evoking high annoyance response when pleasantness level equaled 1) would be lower if an individual perceived the birdsong or stream sound to be pleasant at 65dBA. Similar to scenarios with dominant road traffic sound, the probability difference increased with *SNR* when *SPL* of road traffic was 55 or 60 dBA if the natural sound was perceived as pleasant. However, the trend would be different when road traffic equaled 65 dBA. The probability difference increased with SNR when SNR was between -9 dB to 0 dB and decreased afterwards for acoustic environment augmented by stream sound. For an acoustic environment augmented by birdsong, the probability difference gradually decreased when SNR increased.



(a)



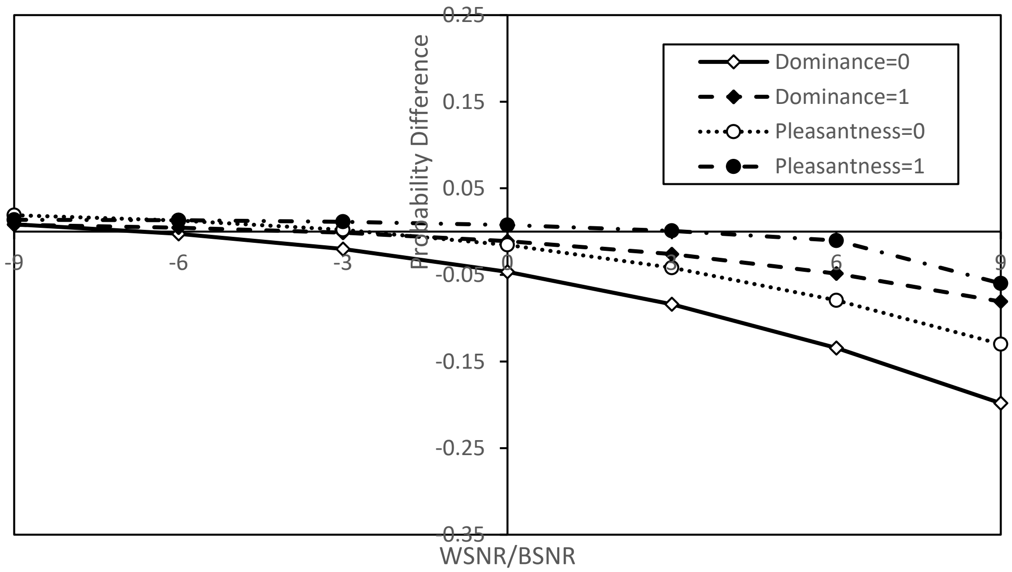
(b)



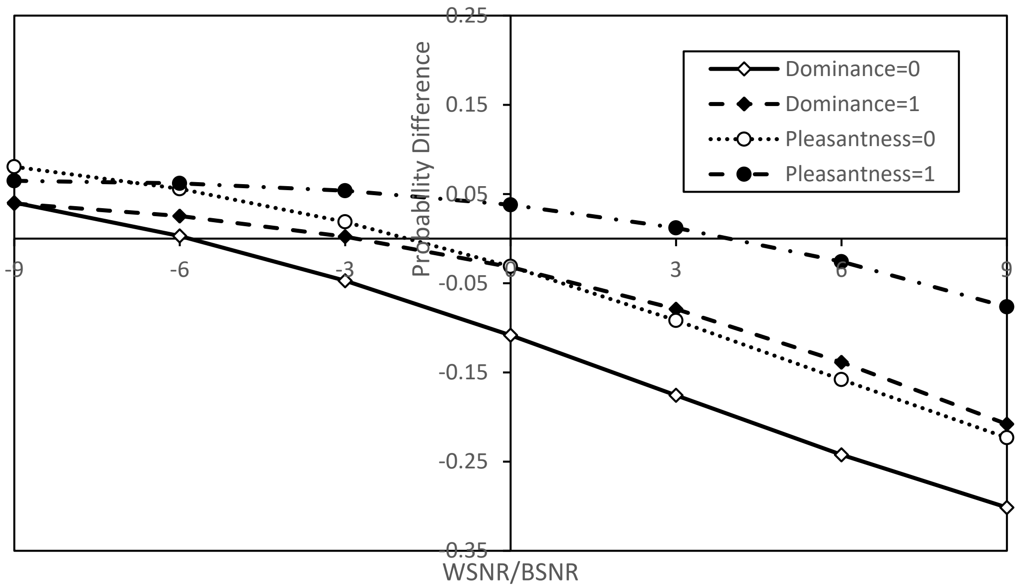
(c)

Fig. 11 The difference in the probability of evoking a high total annoyance response for sound environments augmented by birdsong or stream sound between different perceived pleasantness levels when the road traffic noise level was at (a) 55dBA, (b) 60dBA and (c) 65dBA

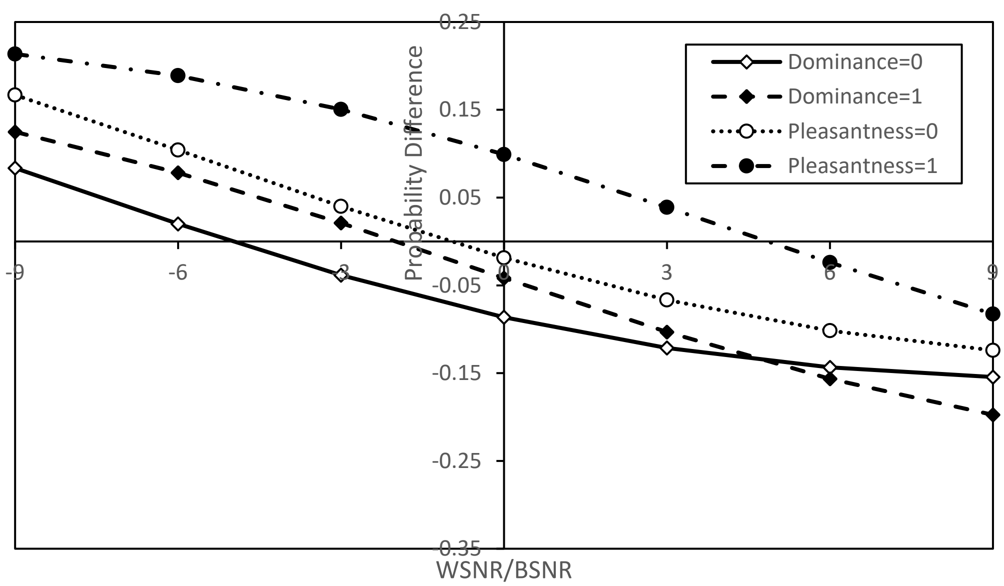
Conceivably, the capability of moderating the total annoyance responses by birdsong and stream sound can be compared using the probabilities of evoking high annoyance response when the acoustic environment was augmented by the natural sounds. As shown in Fig. 12, stream sound would perform better in terms of annoyance moderation at lower SNR, and vice versa at higher SNR. However, the point (SNR) at which birdsong would begin to perform better than stream sound depended on whether road traffic was perceived as a dominant sound source, the pleasantness level of the natural sound augmenting the acoustic environment, as well as traffic sound level. At traffic sound level 55 dBA, the points were at SNR≥-6, SNR≥-3, SNR≥0 and SNR≥6 when DOM equaled 0, DOM equaled 1, PLBird and PLStream equaled 0, and PLBird and PLStream equaled 1. Meanwhile, the points were at SNR≥-3, SNR≥0, SNR≥0 and SNR≥6 at traffic sound level 60 or 65 dBA.



(a)



(b)



(c)

**Probability Difference = Probability of evoking high annoyance response when the acoustic environment was augmented by birdsong - Probability of evoking high annoyance response when the acoustic environment was augmented by stream sound*

*** Probability difference of a positive value signifies that stream sound performed better in terms of annoyance moderation, and vice versa*

Fig. 12 The difference in the probability of evoking a high total annoyance response for between sound environments augmented by birdsong and stream sound when the road traffic noise level was at (a) 55dBA, (b) 60dBA and (c) 65dBA

Besides, the relative contribution of two independent variables on the total noise annoyance can be determined from the absolute value of the ratio of their coefficient values in the models by keeping the total annoyance rating constant. The effects of not perceiving road traffic as a dominant sound source in an acoustic environment containing birdsong/stream sound were equivalent to that as a result of raising the road traffic sound level by 2.47 dB (i.e. 0.8085/0.3276) / 3.39 dB (i.e. 1.0645/0.3144). The effect of raising the *SPL* of road traffic by 1 dB could be compensated by reducing the *SPL* of birdsong by 6.94 dB (i.e. 0.3276/0.0472), or stream sound by 2.39 dB (i.e. 0.3144/0.1315).

4 Discussions and Conclusion

To our best knowledge, this study was the first attempt to formulate hybrid annoyance prediction models comprising both physical factors and perceived dominance of traffic sound and pleasantness of the birdsong/stream sound as perceptual factor. Separate models for birdsong and stream sound have been formulated as their principal mechanisms involved in mitigating noise annoyance are quite different (Zhao et al., 2020). The perceived dominance of traffic sound in the acoustic environment augmented by birdsong/stream sound, as well as the pleasantness of birdsong/stream sound would affect their noise annoyance moderation capabilities. Other interesting observations arising from the findings of this study are going to be discussed in the followings.

Unlike most previously formulated prediction models which investigated the annoyance response of combining two unwanted sounds (Pierrette et al., 2012; Marquis-Favre et al., 2021), this study successfully developed models for the combination of a wanted sound (i.e. birdsong/stream sound) and an unwanted sound (i.e. traffic sound). Results from our models suggested that the totally annoyance response could be reduced by augmenting the acoustic environment with traffic sound by birdsong or stream sound. In fact, previous studies (Jeon et al., 2010; Hao et al., 2016) also suggested similar results. However, the advantage of the formulation of annoyance prediction model is that it can help to predict the performance of the soundscape in terms of annoyance response. In this sense, the models should be useful for soundscape or acoustic environment design as designers may want to know the performance of the soundscape quantitively.

The physical factors included in the models were the sound pressure level of traffic sound and the signal-to-noise ratio between birdsong/stream sound and the traffic sound. This was similar to the energy difference model for predicting the total annoyance response of two noises in previous studies (e.g. Morel et al., 2012). On the other hand, the successful inclusion of perceived sound dominance and pleasantness into the energy difference models containing only physical variables significantly improved the goodness-of-fit of the models. The inclusion of both physical and perceptual variables into the prediction models better portray the noise annoyance moderation effects of birdsong and stream sounds. These results further confirmed that perceived dominance and pleasantness were important factors for good soundscape quality (Pérez-Martínez et al., 2018). However, our study has gone one step further to reveal the quantitative relationship between total annoyance response, and the perceived dominance and pleasantness by means of annoyance model formulation, which has not been reported before. Above all, the inclusion of both physical and perceptual variables into the prediction models better portray the noise annoyance moderation effects of birdsong and stream sounds.

It was also revealed in this study that the likelihood of evoking a high annoyance response would be lowered if an individual did not perceive road traffic as a dominant sound source. This is inline with the previous study suggesting that higher acoustic comfort could be resulted if the first dominant sound was nature-related (Ren, 2023). Our findings also showed that employing pleasant birdsong and stream sound to augment the acoustic environment with traffic sound could help lower the likelihood of evoking a high total annoyance response, which provide supplementary valuable insights on total annoyance responses as earlier findings only pertained to other soundscape descriptors. For instance, soundscape perception was improved by adding pleasant birdsong or water sound (Brungart, 2001; Hong et al., 2020). In fact, our models did not only suggest how perceived dominance of traffic sound and pleasantness of the natural sounds affected the total annoyance response, but also helped to reveal some direct linkage between perceptual factors and physical factors that were seldom reported in previous studies. It was found that the effects of perceived dominance on the total annoyance moderation effect of birdsong or stream sound varied with both *SNR* and road traffic sound level.

However, there are some limitations on the usefulness of the results in this study. First, the results were obtained from a small group of participants aged between 20 and 25 years old. Further studies should be conducted using a larger sample with wider age ranges. Second, the birdsong adopted in this study was from dawn chorus of multiple bird species. We did not differentiate among different types of birdsong. Depending on the harmonics and vocal properties of different species, birdsong is not always perceived pleasant (Pérez-Martínez, et al., 2018). Consequently, it should be cautious when attempting to generalize these results. Third, it is of paramount interest to include other factors such as visual environment, as well as other natural sounds, in order to reveal a more holistic picture of the annoyance responses induced when the acoustic environment with road traffic noise is augmented by natural sounds. This is because noise annoyance perception is a complex phenomenon influencing by not only acoustical factors, but also non-acoustic factors (e.g. experience and knowledge about noise, visibility of noise source, and quality of living environment). Fourth, while self-reported noise sensitivity was considered less reliable than noise sensitivity revealed by noise-sensitivity-questionnaire (e.g. Schutte et al., 2007), it was adopted in this study and the expected association between noise sensitivity and noise annoyance was still obtained (i.e. individuals who were more sensitive to noise would tend to report a higher noise annoyance rating). However, it is recommended to adopt noise-sensitivity-questionnaire to reveal individual's noise sensitivity in future studies as they should be more reliable. Fifth, participants were "tuned in" to the sound clips by the design of the experiments rather than given the choice to tune out, as people in the field would have the discretion to do so (Truax, 1984). The noise annoyance data collected under laboratory conditions should be interpreted with caution. Despite the limitations, the findings and formulated model in this study should contribute to the body of research regarding the role of natural sounds in moderating noise annoyance responses in an acoustical environment containing road traffic noise.

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