https://doi.org/10.1016/j.apacoust.2017.06.020.

Developing a multivariate model for predicting the noise annoyance responses due to combined water sound and road traffic noise exposure

T. M. Leung, C.K. Chau†, S.K. Tang, J.M. Xu

Department of Building Services Engineering,
The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR

†Corresponding author: C.K. Chau

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong SAR, Tel no: (852)-2766-7780; Fax no: (852)-2765-7198; e-mail: chi-kwan.chau@polyu.edu.hk

Abstract

People in an urban environment are exposed to different types of natural and man-made sounds. Human sound perceptions due to exposure to a single noise source, in particular road traffic and aircraft noises, have been investigated for a long time. However, only very few studies have been focused on exposure to a combination of sound sources. Also, there is a lack of multivariate models that can help to predict the preferences or annoyance responses as a result of adding a wanted sound to an unwanted sound. Accordingly, this study aimed at developing a multivariate model to predict the probability of invoking a high noise annoyance response due to combined water sound and road traffic noise exposure. A series of laboratory experiments were performed. Participants were presented with a series of acoustical stimuli before being asked to assign their annoyance ratings. Results suggested that other than acoustical properties like sound pressure levels, personality traits were found to exert considerable influences on the maximum likelihoods of the model prediction and thus should not be excluded from the model specification form. Also, the quality of the acoustical environment could be improved by adding water sounds to road traffic noises at high levels. The capability of stream sound to moderate noise annoyance was found to be slightly stronger than that of fountain sound. In addition, the formulated multivariate model enables to reveal the tradeoff decisions performed by people. An increase in the SPL of road traffic noise by 1 dB was considered to be equivalent to a reduction in the SPL of water source by 1.7 dB for a given probability value. Results arising from this study should provide valuable insights on understanding how humans respond to the combined water sound and road traffic noise exposure.

Keywords: noise annoyance; soundscape; water sounds; sound masking

1. Introduction

People in an urban environment are often exposed to acoustical environments containing multiple sound sources. Some are wanted sounds that people prefer [1], e.g. natural sounds including water sound and bird songs [2]. Some are unwanted sounds or noises that people do not prefer, e.g. road traffic noise [3]. However, annoyance responses have quite often been assumed to be only induced by a single dominant noise source, e.g. road traffic or aircraft noises. Models have been formulated to predict the noise annoyance responses caused by aircraft noise， railway noise or road traffic noise [4–9]. In fact, annoyance may not be only induced by a single sound source. Exposure to two noise sources (e.g. road traffic and railway) may invoke more extensive reactions than exposure to a single noise source at the same sound pressure level [10].

A number of empirical models have been formulated to predict the effect of exposure to two or more types of unwanted sounds on human sound perceptions. Amongst all the unwanted sounds, transportation noises in particular road traffic noises have always been captured the most attention. Physical models and perpetual models have frequently been employed for describing the annoyance responses due to transportation noise exposure.

Physical model operates on the 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. A model with the sound levels of two individual noise sources as explanatory variables was found to perform as good as that with the global sound level of the combined sound environment as an explanatory variable in predicting the total annoyance responses due to combined aircraft and traffic noise exposure [11]. An empirical model with the sound levels of two noise sources as an explanatory variable was shown to be able to reasonably predict the overall dissatisfaction due to combined residential noise exposure [12]. In addition to sound levels of individual sources, differences in sound levels between two sound sources (i.e. signal-to-noise ratio) were also introduced as an additional explanatory variable for predicting the total annoyance responses due to combined industrial noise exposure [13].

Perpetual models aim to predict the total annoyance responses due to combined noise exposure based on a function of the annoyance response or loudness of individual noise sources. For example, dominance model assumes that the noise annoyance due to combined noise exposure is equal to or lower than the annoyance responses due to the most annoying noise source within the combined sources [14]. It was successfully applied in predicting the annoyance responses due to combined aircraft and road traffic noise exposure in Vietnam where road traffic noises were the dominant noise sources [15]. On the other hand, Miedema [16] developed an annoyance-equivalents model to predict the total annoyance responses due to combined noise source exposure by first transforming the annoyance responses due to individual noise sources to an equivalent scale. This model was later successfully applied by Lee et al. [17] to predict the total annoyance responses due to combined construction noise exposure. The model was also modified by Alayrac et al. [18] for portraying the total annoyance responses due to exposure to a combination of background noises and industrial sound having a main spectral component.

However, a majority of the multivariate models developed so far only targeted at predicting the total annoyance responses due to exposure to a combination of unwanted sounds [19,20]. There is a lack of multivariate models that can be used to predict the effects of adding wanted sounds to unwanted sounds on human sound perceptions, e.g. adding water sounds to unwanted road traffic noises.

Sounds arising from water features have been widely perceived as an effective means for enhancing urban soundscape in open spaces especially in urban parks [21–23]. In addition, water sounds have often been proposed to be used for masking unwanted sounds like road traffic noise [22,24,25]. However, water sounds might not benefit the overall quality of urban soundscape when the sound level of road traffic was high, e.g. 70 dBA [26]. Among all types of water sounds, fountain sound and stream sound were the widely studied in the urban soundscape environment perception, e.g. [22,27,28]. Both types of water sounds can improve the sound quality under certain operating conditions. The operating conditions vary with the type of sound quality parameters in focus. For instance, the level of fountain sounds in urban parks needed to be 5 -10 dB higher than that of road traffic noise in order to reduce its perceived loudness [29]. The level of water sound should be at least 3 dB lower than that of road traffic in order to increase the preference ratings of the acoustic environment [24,25,30]. However, it is still not clear how the differences in sound levels between two sources will affect sound perceptions, and how the total annoyance responses vary with the exposure to different combinations of water sound and road traffic noise at high noise levels.

Other than acoustical properties, some personality traits are anticipated to exert influences on annoyance responses. For instance, people rating themselves as sensitive to noises are usually more annoyed by noises [31–37]. Although the foregoing factors exert influences on the preferences/annoyance responses due to combined water and road traffic sound exposure, results were usually derived from pairwise comparisons [e.g. 21,22,28]. It lacks quantitative information for revealing the relative influences of individual factors on total annoyance responses due to combined water and road traffic sound exposure.

Of particular interest of this study is to explore whether annoyance responses due to exposure to high road traffic noise levels will be moderated by adding water sounds. Accordingly, the first objective is to explore whether the physical model forms commonly employed for predicting the total annoyance responses due to exposure to two unwanted sounds are appropriate for predicting the total annoyance responses due to exposure to a combination of road traffic noises (unwanted sound) and water sounds (wanted sound). Second, this study aims to formulate a multivariate model that can help predict the effect of acoustical properties and personality traits on the probability of invoking a high annoyance response due to combined water and road traffic sound exposure. Finally, it aims to reveal the relative influences of acoustical properties and personality traits on the total annoyance responses.

2. Methodology

2.1. Preparation of acoustical stimuli

A series of laboratory experiments was set up to determine the extent of human noise annoyance that could be moderated by adding water sound to the acoustic environment containing high road traffic noise levels. Participants were presented with a series of acoustical stimuli before being asked to assign the total annoyance ratings. The total annoyance rating corresponds to the extent of disturbance for reading activities caused by the combined sound exposure. The combined sound stimuli were generated from a pure road traffic noise source and a water sound recorded in advance. The sample of road traffic noise was extracted from a 30-min record of a busy trunk road, while the samples of fountain sound and stream sound were extracted from the sound clips purchased from a professional audio effect website (www.prosoundeffects.com). Software Audacity 2.0.5 was employed to generate 30-s combined sound clips by mixing sound clips containing water (stream/fountain) with those containing road traffic sounds. The spectral properties of the individual and combined sound sources were analyzed using the spectrum analyzer Bruel & Kjaer Type 2144 and a Head and Torso Simulator (HATS). The HATS embracing a head mounted on a torso represents the international average dimensions of an adult. A low-impedance headphone (64 Ω) of Model HD 280 Pro made by Sennheiser, which has an ambient attenuation of up to 32 dB, was used in the experiments so as to minimize sound spillage from outside. The HATS was equipped with two microphones near the ear region. The sound signals received by the microphones were transmitted to an analyzer for analyzing their acoustical properties. Immediately before performing the experiments, the sound signals from the sound clips were input into the simulator via the headphone to measure the sound levels that would have been heard by a participant via the headphone.

2.2. Experimental design and questionnaire survey

Stream sound and fountain sound were the two types of water sound selected for this study. In this study, 3 sound clips of 30-s each at global sound pressure levels (SPLs) of 65 dBA, 70 dBA and 75 dBA respectively were generated for each type of water source. In addition, 36 sound clips of 30-s each were generated for the combined sounds. The global SPLs of the combined sound clips were also fixed at 65 dBA, 70 dBA or 75 dBA, while the water signal-to-noise ratio (*WSNR*) of the two sound sources increased from -9 to 6 dB, in a step of 3 dB. *WSNR* is the difference in sound pressure levels between water source and road traffic. A negative *WSNR* value denotes that the SPL of road traffic is higher than that of water source, and vice versa.

All the experiments were carried out in a study room located in the Department of Building Services Engineering in the Hong Kong Polytechnic University. Participants were asked to sit in front of a desk and read magazines as if they were reading for leisure at home. 30-s auditory stimuli were presented to the participants. After presenting a stimulus, each participant was given 15s to assign his/her preference or total annoyance ratings in a structured questionnaire form before presenting with the next stimulus. The entire questionnaire was divided into two sections. The first section aimed at eliciting an individual's preference ratings for the two types of water sound using a 21-point scale (Graded -10 to 10; where "-10" means "*Extremely not prefer*" and "10" means "*Extremely prefer*"). The second section aimed at eliciting the total annoyance ratings for exposing to a combined sound of water and road traffic. Participants were also asked to assign their total annoyance ratings for being exposed to the combined sounds using an 11-point scale (Graded 0 to 10; where "0" denotes "*Not annoyed at all*" and "10" denotes "*Extremely annoyed*"). In addition to the preference and annoyance rating assignments, participants were also asked to report their personal characteristics including their self-rated noise sensitivity levels using a 5-point scale (Graded 1-5; where "1" denotes "*Not sensitive at all*" and "5" denotes "*Extremely sensitive*").

Without performing any factorial design, 42 sound clips (i.e. 6 + 36) were required to present to each participant. However, past experience suggested that the quality of responses may degrade if participants are asked to rate all the sound clips continuously within a single experimental session. To circumvent this shortcoming, the entire set of experiments was divided into two sessions. For each session, each participant was only required to assign preference ratings to 3 sound clips containing individual water sources and assign total annoyance ratings containing 21 sound clips of the combined sources. Participants were only required to take part in one of the experimental sessions. However, they were also encouraged to take part in another session within a week after completing the first session. For those returning participants, they were required to answer the questions in relation to personal particulars in the second session again.

3. Results

92 participants were successfully recruited to take part in the experiments, and 28 of them took part in both experimental sessions. A supermarket cash coupon of HK$50 (~US$6.5) in value was given as a reward to each participant after successfully completed a full session of the experiments. Table 1 shows the personal characteristics of the participants. Most of the participants were university students and half of them were males.

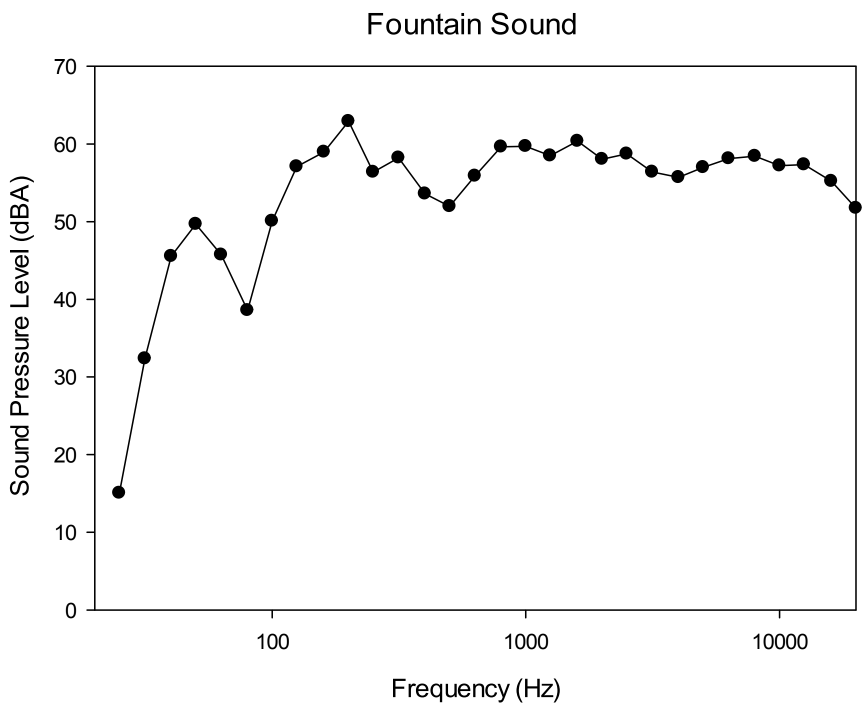
Table 1

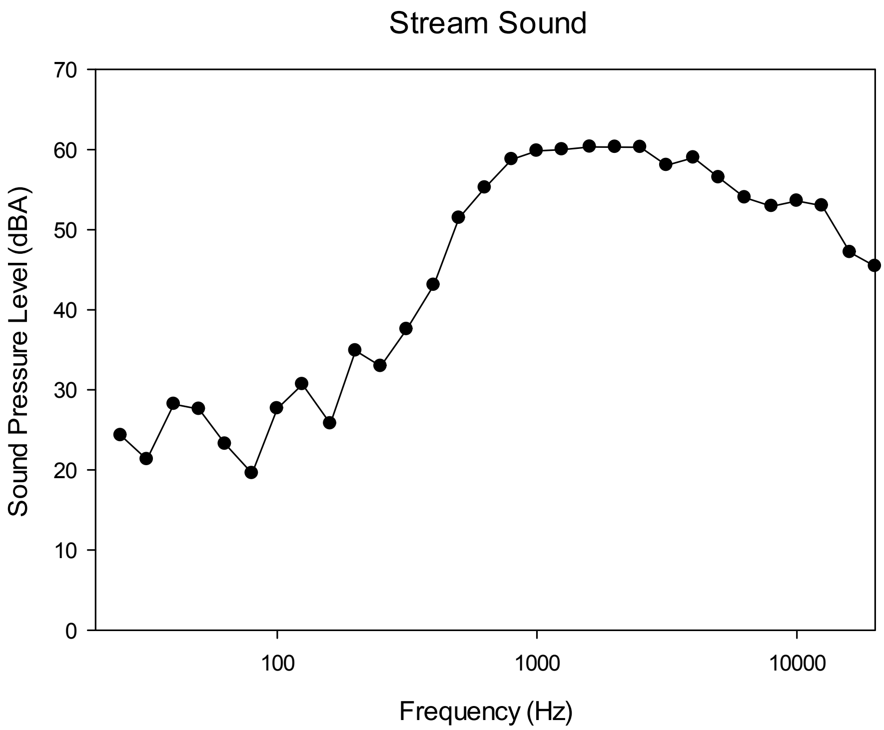
Personal characteristics of the participants

Gender	*Male*	46
	Female	46
	Mean	(Standard deviation)
Age (years)	20.9	(1.9)
Self-rated Health Status	3.4	(0.8)
Noise Sensitivity	3.3	(0.8)

3.1. Acoustical Characteristics of Stimuli

Fig.1 shows the spectra of the studied fountain sound, stream sound and road traffic noise at 70 dBA. It can be seen that the road traffic noise was of higher energy level at low frequency range (25Hz to 500 Hz) and lower energy level at high frequency range (above 4000 Hz). In contrast, the stream sound was of lower energy level at low frequency range while higher energy level at high frequency range, and its energy level at low frequency range was substantially lower than that of fountain sound. Noticeably, the energy levels at different frequencies were more uniformly distributed for combined sounds than for two sounds in isolation as the combined spectra leveled off over a wide frequency range (see Fig. 2).





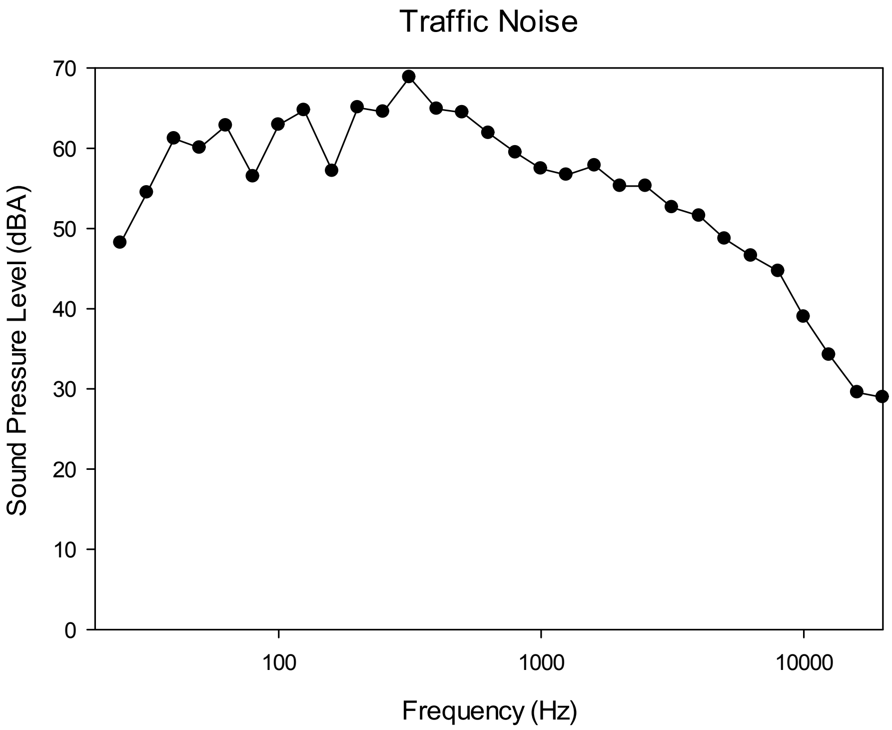


Fig. 1 Spectra of fountain, stream and road traffic sound at 70 dBA

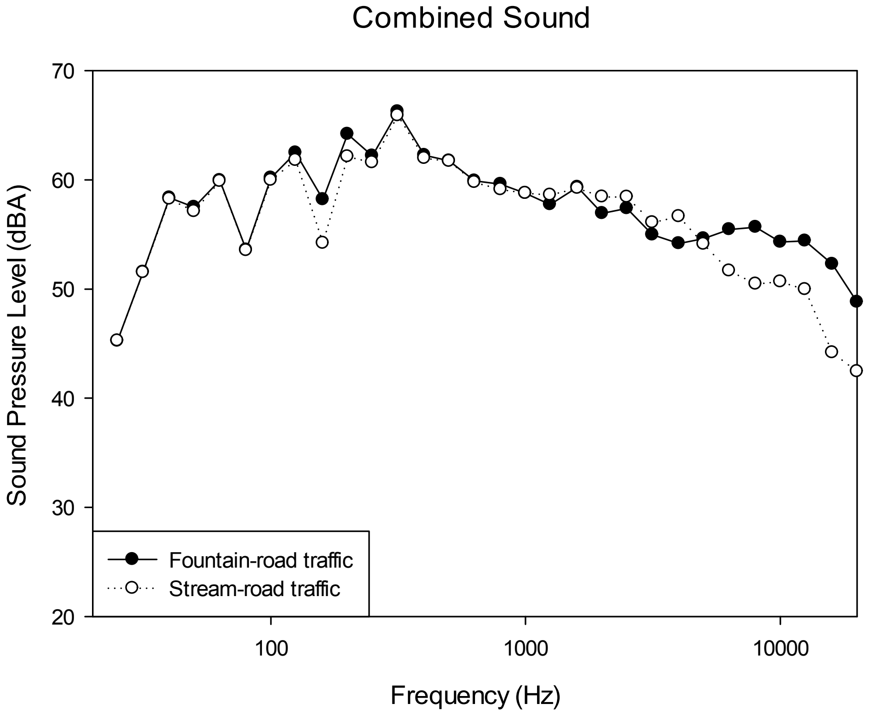
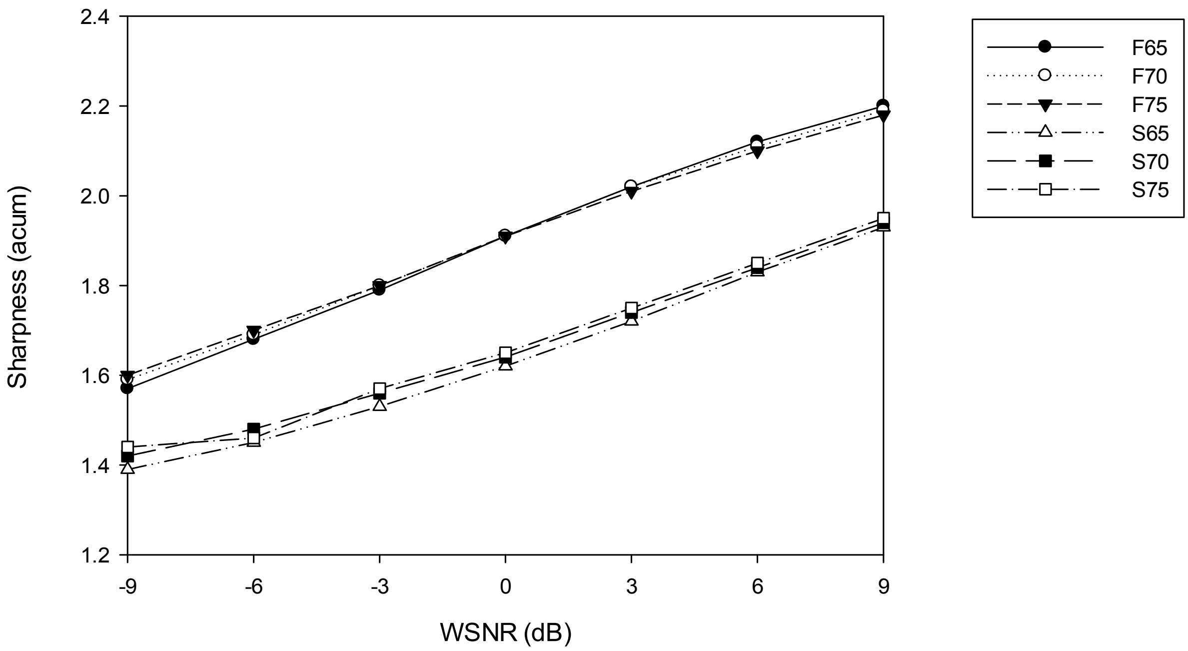
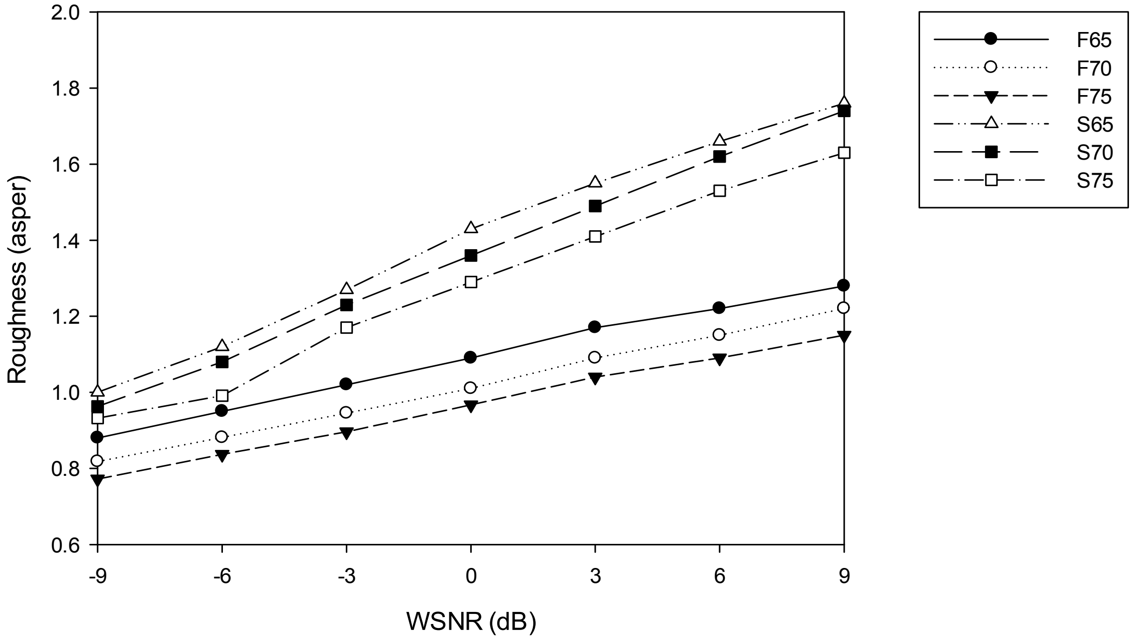
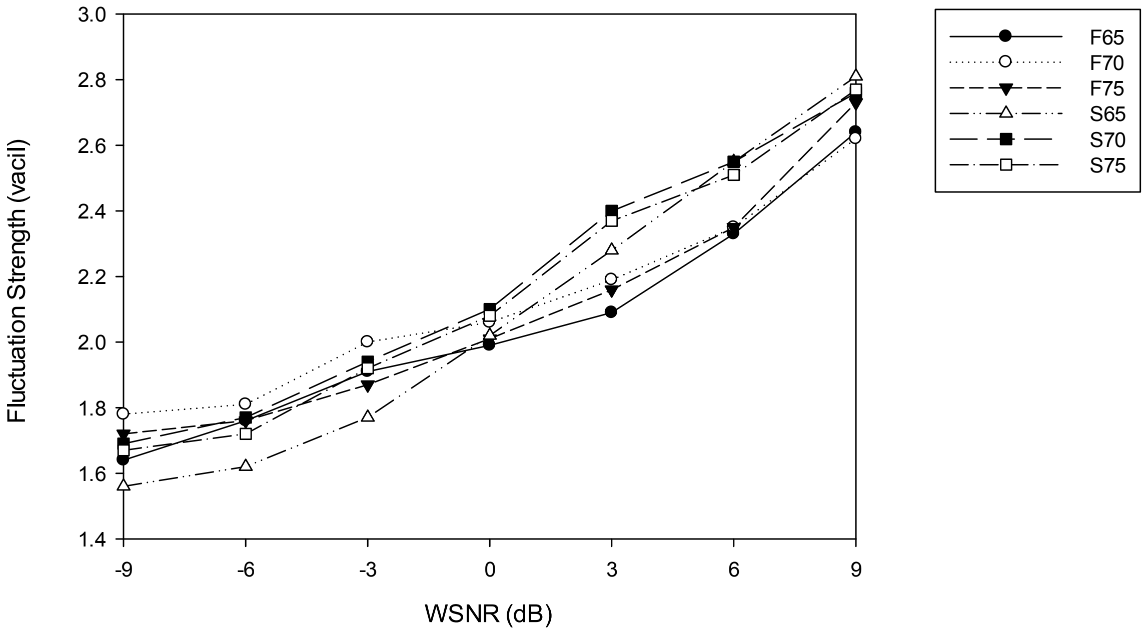


Fig. 2 Spectra of combined stream-road traffic and fountain-road traffic sound at 70 dBA

In addition, the psychoacoustic parameter values of the combined sounds were also determined. Fig. 3 shows the sharpness, roughness and fluctuation strength values of the combined sounds at different *WSNR*s and global sound pressure levels. Significant differences in sharpness and roughness values were also found between these two types of combined sounds (independent t-tests; mean difference coefficient: 0.535 and 0.608 respectively; $p<0.01$). The sharpness values of the combined fountain and road traffic sound were higher than those of the combined sound of stream and road traffic, while the roughness values of the former were lower. However, no significant differences in the fluctuation strength values were observed between the two types of combined sounds (independent t-tests; $p>0.05$). Also, *WSNR* was strongly correlated with sharpness, roughness, and fluctuation strength (with a correlation coefficient of 0.839, 0.733 and 0.964 respectively). This suggests that *WSNR* and sharpness/roughness/fluctuation strength should not be input together as explanatory variables when formulating a multivariate model.


Sharpness (acum)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
-9
-6
-3
0
3
6
9
WSNR (dB)
F65
F70
F75
S65
S70
S75


Roughness (asper)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
-9
-6
-3
0
3
6
9
WSNR (dB)
F65
F70
F75
S65
S70
S75



**F – Fountain sound added to traffic noise; S – Stream sound added to traffic noise; Numeric value after "F" or "S" – Global sound pressure level in dBA*

Fig. 3 Relationships between psychoacoustic parameters and WSNR of the combined water-traffic sound

Fig.4 shows the mean total annoyance ratings for different *WSNR*s at global SPLs of 65, 70 and 75 dBA. The mean total annoyance ratings remained roughly the same at a global SPL of 65 and 70 dBA but were different when *WSNR* laid between -3 and 6 dB. The mean total annoyance ratings of the combined water and road traffic sounds dropped by 18.7 to 28.1% at the global SPLs of 65 and 70 dBA when the WSNR lied between 0 and 3. This suggested that the threshold *WSNR* could be one of the independent variables in the formulation of models for predicting the total annoyance responses due to combined water and traffic sound exposure. Meanwhile, the mean total annoyance ratings assigned to the scenario in which fountain sound was added to road traffic noise were higher than those assigned to the scenario in which stream sound was added (independent t-tests; mean difference: 0.556; $p<0.0001$). Stream sound had a stronger capability than fountain sound to lower the probability of invoking a high total annoyance response.

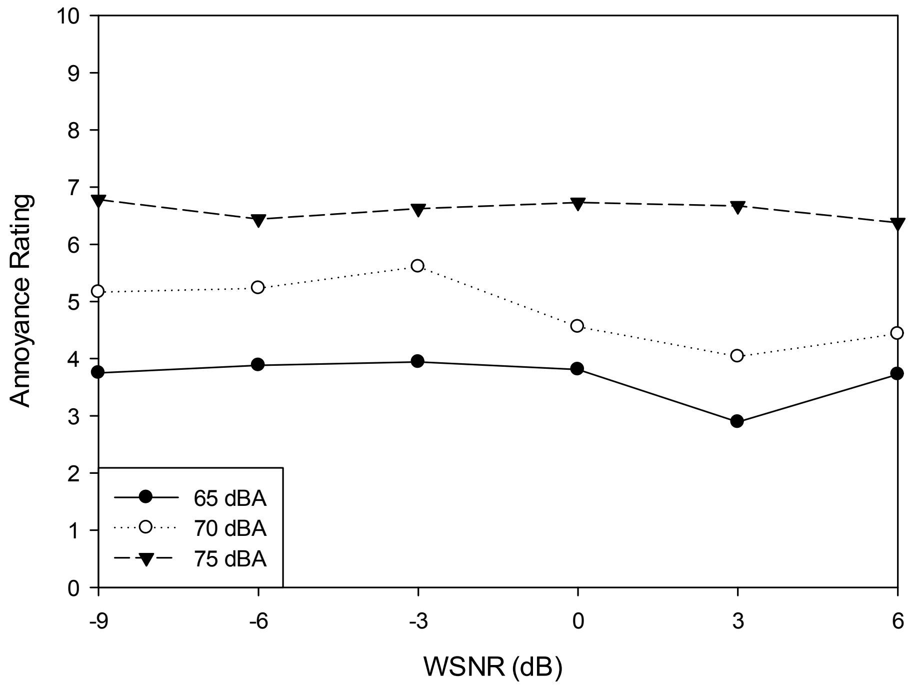


Fig. 4 Mean total annoyance ratings for different WSNRs at three different global SPLs

3.2. Model formulation

Apart from revealing the bivariate relationships with total annoyance responses, it is one of the major objectives of this study to construct a multivariate model to predict the total annoyance responses due to combined water and road traffic sound exposure. Three different physical model forms commonly used for predicting combined unwanted sound exposure were checked against their validity of use. The three model forms investigated, including energy summation model, independent effects model and energy difference model, were evaluated in terms of their maximum likelihood in predicting the probability of invoking a high total annoyance response. In this study, the form of energy difference model was modified by removing the absolute sign from the variable ”Difference in SPLs between two sources” so as to adjust for the differences in nature of the combined sounds, i.e. one contains a wanted and an unwanted sound source while the other contains two unwanted sound sources. To facilitate further analysis, the collected total noise annoyance response data were re-grouped into three categories: “Low annoyance response” (“0”; original rating “0”-“4”), "Moderate annoyance response" ("1"; original rating "5"-"7") and "High annoyance response" ("2"; original rating "8"-"10"). Given that stochastic models can provide more valuable information than deterministic models, ordered logit model forms were used to fit the high noise annoyance response data:

$$Z = f(SPL) \quad (1)$$

where Z is the logit function; SPL is the factor(s) related to the SPLs of the combined sources.

Table 1 shows the regression results of the three different model forms together with their McFadden ρ^2 values. The McFadden ρ^2 values for energy summation, independent effects, and modified energy difference model forms were very similar (i.e. 0.133, 0.134 and 0.135 respectively). The "Modified energy difference model" gave the highest McFadden ρ^2 value, and thus the highest maximum likelihood values in predicting high total annoyance responses. Despite so, only low McFadden ρ^2 values were obtained for all these three models, suggesting that all these models could only fit the response data moderately.

Table 1

Regression results of three different model forms

Model Form	**Regression results**	**Cut points**	**McFadden ρ^2**
Energy summation	$Z = 0.271L_T$	17.752; 20.885	0.133
Independent effects	$Z = 0.192L_{TN} + 0.085L_{WS}$	16.555; 19.692	0.134
Modified energy difference	$Z = 0.271L_T - 0.028D$	17.844; 20.989	0.135

*Note: L_T: Global SPL of the acoustic environment; L_{TN}: Traffic noise level; L_{WS}: Water sound level; D: Difference between traffic noise and water sound.

3.3. Refined models

In addition to sound pressure levels, other acoustical properties like type of water sounds and *WSNR* are anticipated to exert considerable influences on the total annoyance responses. Also, some personality traits such as self-rated noise sensitivity have been shown to influence total annoyance responses. Accordingly, the refined model form becomes:

$$Z = f(SPL, Threshold, Type, PT) \quad (2)$$

Where *Threshold* is a variable denoting the threshold *WSNR*, *Type* is the type of water sound added to road traffic noise and *PT* is the variable related to personality traits.

Table 2 shows the regression results of three different model forms after adding the relevant acoustical factors (i.e. threshold *WSNR*, *Threshold*, and type of water sound added to traffic noise *Type*) and personality traits as explanatory variables. The McFadden ρ^2 values of the energy summation, independent effects and modified energy difference model form were found to be 0.144, 0.147 and 0.141 respectively after adding the acoustical variables. These correspond to the increase in ρ^2 values by 8.3%, 9.7% and 4.4% for the three model forms respectively. Due to the multi-collinearity problem, the variable *WSNR* was subsequently dropped from the modified energy difference model form. Of the three model forms, independent effects model containing two additional acoustical variables (i.e. *WSNR* and type of water sound added) gave the highest McFadden ρ^2 value.

In addition, McFadden ρ^2 values of the models increased considerably by adding the personality traits (i.e. 0.178, 0.182 and 0.176 for energy summation, independent effects and modified energy difference models respectively). The McFadden ρ^2 values increased by 23.6%, 23.8% and 24.8% for the three model forms respectively when compared with the models containing only acoustical variables.

Table 2

Regression results of three different model forms after adding the relevant acoustical properties and personality traits

Model Form	**Regression results**	**Cut points**	**McFadden ρ^2**
With the acoustical properties of the combined sources and			

personality traits			
Energy summation	$Z = 0.272L_T - 0.529Threshold - 0.453Type +$	19.941; 23.303	0.178
Independent effects	$Z = 0.170L_{TN} + 0.100L_{WS} - 0.618Threshold -$	18.798; 22.178	0.182
Modified energy difference	$Z = 0.287L_T - 0.031D - 0.455Type + 0.571Ge$	17.771; 20.944	0.176
With the acoustical properties of combined sources only			
Energy summation	$Z = 0.258L_T - 0.542Threshold - 0.432Type$	16.518; 19.711	0.144
Independent effects	$Z = 0.160L_{TN} + 0.096L_{WS} - 0.633Threshold -$	15.409; 18.619	0.147
Modified energy difference	$Z = 0.274L_T - 0.029D - 0.434Type$	17.771; 20.944	0.141

*Notes: *Gender*: Gender, which takes the value of 0 if an individual is a male, and otherwise 1; *Sen*: Self-rated noise sensitivity level of an individual; *Type:* Type of the water sound, which takes 1 if stream sound, otherwise 0; *Threshold:* Threshold, which takes the value of 1 when WSNR is equal to 0-3dB and the global SPL is lower than or equal to 70 dBA, otherwise 0.

As independent effects model gave the highest maximum likelihood value, the following discussions are only confined to this model form (with all acoustical and personality factors being added). The effect of an individual factor on the total annoyance response can be revealed from its corresponding coefficient value. A positive coefficient value indicates that the probability of invoking a high annoyance response increases with the value of the studied factor, and vice versa. It can be seen that the probability of invoking a high total annoyance response increased with the

SPL of water source or road traffic noise. Generally, road traffic noise level was found to exert a larger influence on total annoyance ratings than water sound level (cf. the coefficient value of traffic noise level = 0.170 > that of water sound level = 0.100). The probability value would drop in case *WSNR* lied within the range of 0-3dB, or if stream sound instead of fountain sound was added to traffic noise. As expected, some personality traits have also been shown to exert influences on the total annoyance responses. Similar to the findings from a majority of annoyance studies, a more noise sensitive individual was found to be more likely to give a high noise annoyance response [39,40]. Besides, our findings also revealed that gender exerted an influence on the probability of giving a high total annoyance response. Females were more likely to give high total annoyance responses.

3.4. Trade-offs between factors

Apart from revealing the effects of individual factors on total annoyance responses, the model can also help determine the trade-off ratios implicitly assigned by the participants given the same probability of invoking a high total annoyance response. The trade-off ratio between two individual factors, i.e. the rate at which an individual is willing to give up one unit of a factor for an increase in one unit of another factor, which is also known as marginal rate of substitution, can be found from the ratio of the two coefficients. For example, an increase in the SPL of road traffic noise by 1 dB was considered to be equivalent to a reduction in the SPL of water source by 1.7 dB (i.e. -0.170/0.100). This suggested that the influence of sound level of road traffic noise on the probability of invoking a high total annoyance response was 1.7 times of that of water sound. Also, *WSNR* between the sound sources lying within the range of 0-3 dB was found to be equivalent to a reduction in traffic noise level by 3.6 dB (i.e. 0.618/0.170) or a reduction in water sound level by 6.2 dB (i.e. 0.618/0.100) when the global SPL was lower than or equal to 70 dBA. An adjustment of 3.9 dB (i.e. 0.665/0.170) in road traffic noise or 6.7 dB in water sound (i.e. 0.665/0.100) should be added to a highly noise sensitive individual in order to achieve the same probability of invoking a high total annoyance response as a less noise sensitive one.

With the formulated model, the probability of invoking a high total annoyance response due to combined water sound and road traffic noise exposure can also be computed. Fig. 4 shows the probability values for different fountain and stream sound levels. The probability values were computed by fixing the road traffic noise level at 65 dBA while keeping other factors at their mean values. It can be seen that the probability value increased with the SPL of stream and fountain, and there was a sudden drop in the probability value when the *WSNR* lied between 0 and 3 dB.

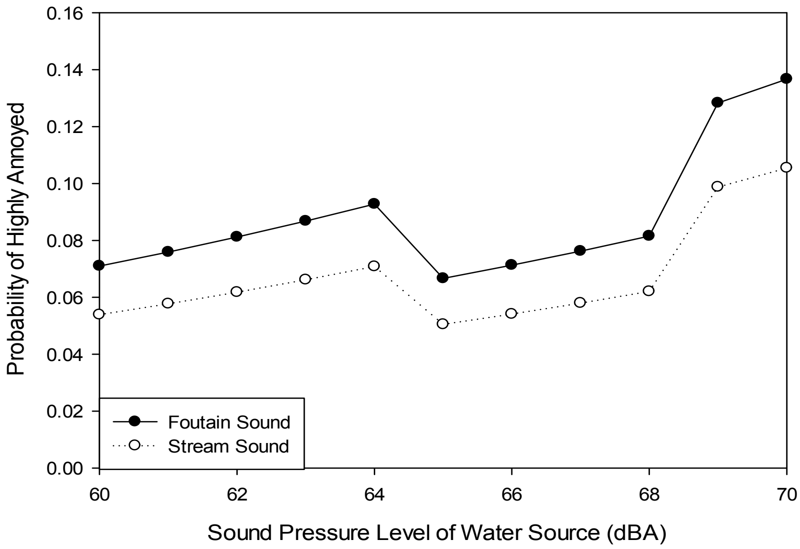


Fig. 4 The probability values of invoking a high total annoyance response for different levels of fountain and stream sound when road traffic noise was at 65 dBA

4. Discussions and conclusion

This study successfully formulated a multivariate model to predict the probability of invoking a high total annoyance response due to exposing to combined road traffic noises and water sound. To our best knowledge, this is also one of the pioneering studies that has successfully formulated a model to predict the probability due to exposure to a combination of both wanted and unwanted sounds. The model form successfully includes not only acoustical factors (e.g. levels of two sound sources), but also personality traits (e.g. noise sensitivity). However, other non-acoustical factors like age, type of tasks undertaken by an individual, and the surrounding environmental conditions had not been added to the model as they were carefully controlled in this study to minimize the confounding effects on the responses. For instance, the effect of the type of activities undertaken by an individual on total annoyance rating had not been explored as all the participants were requested to perform the same task i.e. reading magazines during experiments. Given most of our participants were undergraduate students, the effects of age and educational attainment on total annoyance responses were not investigated in our models. Despite so, personality traits including noise sensitivity and gender were found to exert considerable influences on the maximum likelihood values of the model prediction (i.e. the maximum likelihood of the model prediction increased by 23%). The prediction power of the physical model forms would be substantially undermined if personality traits were excluded. Therefore, it is vital to include personality traits in the model specification in order to give a better prediction. Also, the formulation of multivariate models enables to reveal the trade-off decisions performed by participants between individual factors. The tradeoff decisions are more related to the real life situation as people are often confronted with multi-criteria decisions in their daily life. Of equal importance is that tradeoff ratios can be used to develop a conversion metrics to translate the annoyance effect caused by a qualitative factor into an objectively measured dB level, e.g. noise sensitivity.

Second, both stream sound and fountain sound were found to be capable of moderating annoyance responses due to road traffic noises. This is in line with the earlier conclusions drawn from bivariate analyses that the average preference ratings would be higher after adding stream or fountain sound to road traffic noises [25]. Based on the findings arising from our model, the capability to lower the probability of invoking a high total annoyance response varied with the type of water sound added. The capability of stream sound was found to be slightly stronger than that of fountain sound (i.e. the probability value of invoking a high total annoyance response would be lower by 4.3% if stream sound was added instead of fountain sound). However, a question arises as to whether some psychoacoustic parameters can be used as a proxy for the type of water sounds in the final model form. Unfortunately, the evidence reported so far is in divergence. Some reported that noise annoyance ratings given by individuals were linearly correlated with psychoacoustic parameters such as sharpness and roughness [41–44], but on the contrary others suggested that noise annoyance was not significantly correlated with psychoacoustic parameters [45–48]. Furthermore, it also depends on the nature of sounds, e.g. sounds with meaning such as traffic sound were less well predicted by psychoacoustic parameters [42,49] when compared with sounds without meaning. Situations may become more complicated when combined sounds are considered.

Finally, there is a “combined sound region” in which human sound perceptions are considerably different from those outside the region. A combined sound region is observed when the SPLs of the two combined sounds are similar, i.e. with a difference of a few dBs. Human sound perceptions within the region are different from those outside the region due to the synergistic effect occurs between two sounds [41]. For instance, the probability of invoking a high total annoyance response has been found to be significantly lower when the sound levels of both sources were similar. This not only occurs in the scenarios involving exposure to a combination of wanted and unwanted sounds [11,18], but also to those involving exposure to a combination of two unwanted sounds [10]. Within the combined sound region, the probability will become higher instead of lower when an unwanted sound is added to another unwanted sound. However, synergetic effects may not be present for all types of combination of sounds, e.g. no synergetic effect was observed when people were simultaneously exposed to sound from gunfire, aircraft, and/or road traffic [50]. The combined region was observed to be present in this study when differences in SPLs of water sound and traffic noise laid between 0 and 3 dB, which is slightly different from the range of values determined from other studies [24,25,30]. Besides, such combined region was only observed at global sound pressure levels of 65 dBA or 70 dBA but not at 75 dBA. Such differences are probably due to differences in the types of human sound perceptions in focus, i.e. noise annoyance vs sound preference. Further studies are needed to explore the differences.

Meanwhile, it is noteworthy pointing out that there are some limitations arising from this study which limit the applicability of the formulated model. First, the applicability of findings is only confined to the global SPL lying between 65 and 75 dBA. Further studies should be performed to reveal whether similar findings can be obtained when the global SPL is lower than 65 dBA or higher than 75 dBA. Sound level of 65 dBA, which has commonly been observed in highly populated city areas [51], could already make people feel “very annoy” [52]. At such high global SPL, high noise annoyance responses would be invoked regardless of whether water sounds were added or not. Thus, the formulated model can be applied to predict how noise annoyance responses can be moderated by adding water sounds to road traffic noise at high levels. For instance, it can be applied to predict the effect on the total annoyance response due to adding water sounds to the acoustical environment of residential dwellings containing high road traffic noise levels. However, it is not applicable for predicting how the sound perceptions will be altered in scenarios which involve adding water sounds to road traffic noises at low levels in relatively quiet open areas. Second, the findings are only applicable for stream and fountain sounds with the particular types of spectral characteristics. As the sound spectra for different types of water sound or even for the same type of water sounds are anticipated to be different, it is not appropriate to generally apply the formulated model to predict total annoyance responses due to exposure to other types of water sound as their sound spectra may be remarkably different. The capabilities of water sounds to improve the quality of sound environment have been shown to vary with their spectral characteristics [27]. Furthermore, the spectral characteristics of the fountain sound employed in this study were similar to those of road traffic noise at the low frequency ranges in which both types of sounds were at high energy levels. This might exert some influences on the total annoyance responses. Further investigations should be carried out by analyzing the spectral characteristics together with other psycho-acoustical properties such as roughness and sharpness. Above all, it is suggested including more types of water sounds and also same types of water sounds but having different spectral characteristics in future studies. With more samples of water sounds being studied, it may be possible to introduce some psychoacoustic factors and spectral characteristics as explanatory variables to make the model more robust. Finally, the findings may only be applicable for people aged between 20 and 25 years. A larger scale study is needed before the results can be extended to the other population subgroups. Above all, the findings arising from this study should provide valuable directions for future research studies in refining multivariate models to portray the human perceptions due to exposure to acoustical environments with wanted sounds being added to unwanted sounds.

Acknowledgements

The authors would like to thank the Research Grant Council in Hong Kong for the funding support through the General Research Grants No: PolyU 5121/13E.

References

[1] Yang M, Kang J. Psychoacoustical evaluation of natural and urban sounds in soundscapes. The Journal of the Acoustical Society of America 2013;134:840–51. doi:10.1121/1.4807800.

[2] Brown AL, Kang J, Gjestland T. Towards standardization in soundscape preference assessment. Applied Acoustics 2011;72:387–92. doi:10.1016/j.apacoust.2011.01.001.

[3] Birgitta Berglund & Thomas Lindvall, editor. Community Noise. Stockholm, Sweden: 1995.

[4] Gille L-A, Marquis-Favre C. Dose-effect relationships for annoyance due to road traffic noise: Multi-level regression and consideration of noise sensitivity. The Journal of the Acoustical Society of America 2016;139:2070–2070. doi:10.1121/1.4950140.

[5] Miedema HM, Oudshoorn CG. Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environmental Health Perspectives 2001;109:409–16.

[6] Miedema HME, Vos H. Exposure-response relationships for transportation noise. http://dx.doi.org/101121/1423927 1998. doi:10.1121/1.423927.

[7] Trollé A, Marquis-Favre C, Klein A. Short-Term Annoyance Due to TramwayNoise: Determination of an Acoustical Indicator of Annoyance Via Multilevel Regression Analysis 2014;100:34–45. doi:10.3813/AAA.918684.

[8] Kim J, Lim C, Hong J, Lee S. Noise-induced annoyance from transportation noise: Short-term responses to a single noise source in a laboratory. The Journal of the Acoustical Society of America 2010;127:804–14. doi:10.1121/1.3273896.

[9] Gille L-A, Marquis-Favre C, Weber R. Aircraft noise annoyance modeling: Consideration of noise sensitivity and of different annoying acoustical characteristics. Applied Acoustics 2017;115:139–49. doi:10.1016/j.apacoust.2016.08.022.

[10] Ohrström E, Barregård L, Andersson E, Skånberg A, Svensson H, Angerheim P. Annoyance due to single and combined sound exposure from railway and road traffic. The Journal of the Acoustical Society of America 2007;122:2642–52. doi:10.1121/1.2785809.

[11] Taylor SM. A comparison of models to predict annoyance reactions to noise from mixed sources. Journal of Sound and Vibration 1982;81:123–38.

[12] Jeon JY, Ryu JK, Lee PJ. A quantification model of overall dissatisfaction with indoor noise environment in residential buildings. Applied Acoustics 2010;71:914–21. doi:10.1016/j.apacoust.2010.06.001.

[13] Morel J, Marquis-Favre C, Viollon S, Alayrac M. A laboratory study on total noise Annoyance due to combined industrial noises. Acta Acustica United with Acustica 2012;98:286–300. doi:10.3813/AAA.918512.

[14] Rice C, K I. Factors affecting the annoyance of combinations of noise sources. Proceedings of the Institute of Acoustics 1986;8:325–32.

[15] Nguyen TL, Nguyen HQ, Yano T, Nishimura T, Sato T, Morihara T, et al. Comparison of models to predict annoyance from combined noise in Ho Chi Minh City and Hanoi. Applied Acoustics 2012;73:952–9. doi:10.1016/j.apacoust.2012.04.005.

[16] Miedema HME. Relationship between exposure to multiple noise sources and noise annoyance. The Journal of the Acoustical Society of America 2004;116:949–57. doi:10.1121/1.1766305.

[17] Lee SC, Hong JY, Jeon JY. Effects of acoustic characteristics of combined

construction noise on annoyance. Building and Environment 2015;92:657–67. doi:10.1016/j.buildenv.2015.05.037.

[18] Alayrac M, Marquis-Favre C, Viollon S. Total annoyance from an industrial noise source with a main spectral component combined with a background noise. The Journal of the Acoustical Society of America 2011;130:189–99. doi:10.1121/1.3598452.

[19] Marquis-Favre C, Morel J. A Simulated Environment Experiment on Annoyance Due to Combined Road Traffic and Industrial Noises. International Journal of Environmental Research and Public Health 2015;12:8413–33. doi:10.3390/ijerph120708413.

[20] Pierrette M, Marquis-Favre C, Morel J, Rioux L, Vallet M, Viollon S, et al. Noise annoyance from industrial and road traffic combined noises: A survey and a total annoyance model comparison. Journal of Environmental Psychology 2012;32:178–86. doi:10.1016/j.jenvp.2012.01.006.

[21] Ren X, Kang J. Effects of the visual landscape factors of an ecological waterscape on acoustic comfort. Applied Acoustics 2015;96:171–9. doi:10.1016/j.apacoust.2015.03.007.

[22] Axelsson Ö, Nilsson ME, Hellström B, Lundén P. A field experiment on the impact of sounds from a jet-and-basin fountain on soundscape quality in an urban park. Landscape and Urban Planning 2014;123:49–60. doi:10.1016/j.landurbplan.2013.12.005.

[23] Pheasant RJ, Fisher MN, Watts GR, Whitaker DJ, Horoshenkov K V. The importance of auditory-visual interaction in the construction of “tranquil space.” Journal of Environmental Psychology 2010;30:501–9. doi:10.1016/j.jenvp.2010.03.006.

[24] Galbrun L, Ali TT. Acoustical and perceptual assessment of water sounds and

their use over road traffic noise. The Journal of the Acoustical Society of America 2013;133:227–37.

[25] Jeon JY, Lee PJ, You J, Kang J. Perceptual assessment of quality of urban soundscapes with combined noise sources and water sounds. The Journal of the Acoustical Society of America 2010;127:1357–66. doi:10.1121/1.3298437.

[26] Hong JY, Jeon JY. Designing sound and visual components for enhancement of urban soundscapes. The Journal of the Acoustical Society of America 2013;134:2026–36. doi:10.1121/1.4817924.

[27] Coensel B De, Vanwetswinkel S, Botteldooren D. Effects of natural sounds on the perception of road traffic noise. The Journal of the Acoustical Society of America 2011;129:EL148-53. doi:10.1121/1.3567073.

[28] Asakawa S, Yoshida K, Yabe K. Perceptions of urban stream corridors within the greenway system of Sapporo, Japan. Landscape and Urban Planning 2004;68:167–82. doi:10.1016/S0169-2046(03)00158-0.

[29] Nilsson ME, Alvarsson J, Rådsten-Ekman M, Bolin K. Auditory masking of wanted and unwanted sounds in a city park. Noise Control Engineering Journal 2010;58:524. doi:10.3397/1.3484182.

[30] You J, Lee PJ, Jeon JY. Evaluating water sounds to improve the soundscape of urban areas affected by traffic noise. Noise Control Engineering Journal 2010;58:477. doi:10.3397/1.3484183.

[31] van Kamp I, Job RFS, Hatfield J, Haines M, Stellato RK, Stansfeld SA. The role of noise sensitivity in the noise–response relation: A comparison of three international airport studies. The Journal of the Acoustical Society of America 2004;116:3471–9. doi:10.1121/1.1810291.

[32] Miedema HME, Vos H. Noise sensitivity and reactions to noise and other environmental conditions. The Journal of the Acoustical Society of America

2003;113:1492–504. doi:10.1121/1.1547437.

[33] Zimmer K, Ellermeier W. Psychometric properties of four measures of noise sensitivity: a comparison. Journal of Environmental Psychology 1999;19:295–302. doi:10.1006/jevp.1999.0133.

[34] Job RFS. Noise sensitivity as a factor influencing human reaction to noise. Noise & Health 1999;1:57–68.

[35] Stansfeld SA. Noise, noise sensitivity and psychiatric disorder: epidemiological and psychophysiological studies. Psychological Medicine Monograph Supplement 1992;22:1. doi:10.1017/S0264180100001119.

[36] Belojević G, Öhrström E, Rylander R. Effects of noise on mental performance with regard to subjective noise sensitivity. International Archives of Occupational and Environmental Health 1992;64:293–301. doi:10.1007/BF00378288.

[37] Linden W, Frankish J, McEachern HM. The effect of noise interference, type of cognitive stressor, and order of task on cardiovascular activity. International Journal of Psychophysiology 1985;3:67–74. doi:10.1016/0167-8760(85)90021-2.

[38] Jeon JY, Lee PJ, You J, Kang J. Acoustical characteristics of water sounds for soundscape enhancement in urban open spaces. The Journal of the Acoustical Society of America 2012;131:2101–9. doi:10.1121/1.3681938.

[39] Paunović K, Jakovljević B, Belojević G. Predictors of noise annoyance in noisy and quiet urban streets. The Science of the Total Environment 2009;407:3707–11. doi:10.1016/j.scitotenv.2009.02.033.

[40] Jakovljevic B, Paunovic K, Belojevic G. Road-traffic noise and factors influencing noise annoyance in an urban population. Environment International 2009;35:552–6. doi:10.1016/j.envint.2008.10.001.

[41] Pedersen E, van den Berg F, Bakker R, Bouma J. Can road traffic mask sound

from wind turbines? Response to wind turbine sound at different levels of road traffic sound. Energy Policy 2010;38:2520–7. doi:10.1016/j.enpol.2010.01.001.

[42] Ellermeier W, Zeitler A, Fastl H. Predicting annoyance judgments from psychoacoustic metrics: identifiable versus neutralized sounds. Inter-noise, 2004.

[43] Ishiyama T, Hashimoto T. The impact of sound quality on annoyance caused by road traffic noise: an influence of frequency spectra on annoyance. JSAE Review 2000;21:225–30. doi:10.1016/S0389-4304(99)00090-9.

[44] Johansson O. Relationship between psychoacoustic descriptors and annoyance: regarding sounds in home environment. Inter-noise, vol. 7, 2000, p. 1669.

[45] Waye KP, Öhrstrom E. Psychoacoustic characters of relevance for annoyance of wind turbine noise. Journal of Sound and Vibration 2002;250:65–73. doi:10.1006/jsvi.2001.3905.

[46] Kaczmarek T, Preis A. Annoyance of Time-Varying Road-Traffic Noise. Arch Acoust 2010;35:383–93. doi:10.2478/v10168-010-0032-2.

[47] Paviotti M, Vogiatzis K. On the outdoor annoyance from scooter and motorbike noise in the urban environment. Science of The Total Environment 2012;430:223–30. doi:10.1016/j.scitotenv.2012.05.010.

[48] Klein A, Marquis-Favre C, Weber R, Trollé A. Spectral and modulation indices for annoyance-relevant features of urban road single-vehicle pass-by noises. The Journal of the Acoustical Society of America 2015;137:1238–50. doi:10.1121/1.4913769.

[49] Fastl H. Features of neutralized sounds for long term evaluation. 17th International Congress of Acoustics (ICA 2001), Rome, Italy: 2001.

[50] Vos J. Annoyance caused by simultaneous impulse, road-traffic, and aircraft sounds: A quantitative model. The Journal of the Acoustical Society of America

1992;91:3330–45. doi:10.1121/1.402823.

[51] The provision of service for the study of health effects of transportation noise in Hong Kong. 2012.

[52] Ouis D. Annoyance from Road Traffic Noise: A Review. Journal of Environmental Psychology 2001;21:101–20. doi:10.1006/jevp.2000.0187.