Testing models for annoyance due to urban road traffic noise combined with tramway noise

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ABSTRACT

Noise annoyance is one of the most significant effects of noise on health for exposures to non-critical sound levels. Due to the expansion and densification of urban areas, residents are exposed to different combined noise sources. In this study, annoyance due to urban road traffic noise combined with tramway traffic noise is assessed under controlled conditions. The urban road traffic is composed of light vehicles, heavy vehicles, buses and powered-two-wheelers. The tramway traffic corresponds to different tramways operating in in-curve configurations. Total annoyance models from literature are tested. Data from a first experiment allow to construct perceptual and psychophysical models of total annoyance. Data from a second experiment was used to estimate the predictive power of these models. The results show that 1) the perceptual models are more efficient to predict total annoyance, and 2) the perceptual dominant source and regression models, constructed using the partial annoyance calculated from recent indicators proposed in literature, are most suitable for predicting annoyance due to combined urban road traffic and tramway noises. These results reveal the superiority of perceptual models against psychophysical models based on noise level, and therefore the importance of improving models for annoyance due to single noise exposure.

Keywords: Annoyance, combined noise exposure, road traffic noise, tramway traffic noise. I-INCE Classification of Subjects Numbers: 63.2, 69.3

1. INTRODUCTION

Noise remains one of the major environmental concerns in Europe. Exposure to transportation noise can lead to noise annoyance. Studies showed that energy-based indices, such as the index L_{den} used for noise maps in Europe, are insufficient to adequately account for noise annoyance due to transportation noise in cities (*e.g.* 1). Tramway networks considered as sustainable transport constitute a supplementary noise source in cities. This leads to combined noise exposure due to urban road traffic and tramway traffic. In recent studies, indicators for the characterization of urban road vehicle pass-by noises and tramway pass-by noises have been proposed. First, an indicator comprising mean loudness, a spectral index and two modulation indices was found to better characterize annoyance due to urban road vehicle pass-by noises (2). For annoyance due to tramway pass-by noises an indicator comprising the sound pressure level and a spectral index has been proven to be adequate (3, 4). Few studies address the issue of noise annoyance due to combined road traffic and tramway noises. Rylander *et al.* (5) conducted a field study on annoyance due to tramway noise and concluded that the difference in acoustical features between road traffic and tramway traffic may play an important role in the formulation of annoyance responses. Miedema and Van den Berg (6) highlighted the contribution of tramway noise to total annoyance due to combined road traffic and tramway noises in a field study. They concluded that specific acoustical features of tramway noise such as squeal noise may have an influence on annoyance. Alim and Zaki (7) carried out a study to investigate annoyance reactions of residents living in buildings facing tramway tracks. They found weak correlations between annoyance and noise exposure characterized by equivalent sound pressure level L_{eq}. This highlights the

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importance to work on such combined noise exposure by considering different indices able to account for various acoustical features of the noise sources in the combination.

In order to investigate noise annoyance due to combined urban road and tramway traffic, two experiments were conducted in laboratory conditions. Experiment A (Exp. A) was carried out in an imaginary context and Experiment B (Exp. B) in a simulated context differing in procedure, apparatus and stimuli. The procedure of Exp. A allows to test different acoustical situations of the combined noises with differences in vehicle types and traffic densities regarding both road and tramway traffic. Exp. B is close to a real context of residents at home. Total annoyance models were constructed using data from Exp. A and were tested using data from Exp. B. Section II briefly describes the experimental methodology of both experiments. Section III presents the testing of models of total annoyance due to the combination of road and tramway traffic noises. More details will be given in a forthcoming paper.

2. COMBINED NOISE EXPOSURE - EXPERIMENTS

2.1 Experiment A - Imaginary context

2.1.1 Noise recording

The urban road vehicle pass-by noises employed in Exp. A to construct the road traffic noise sequences stemmed from recordings carried out *in situ* by Morel *et al.* (8) in Lyon and its suburbs. The tramway pass-by noises in in-curve operating configurations used in Exp. A stemmed from *in situ* recordings made by Trollé *et al.* (3) in Lyon. Both urban road vehicle pass-by noises and tramway pass-by noises were recorded using the ORTF technique. This recording technique used for stereophonic sound reproduction in laboratory is known for its good representation, readability, plausibility and overall reproduction quality for fixed and moving noise sources (9). The different urban road and tramway traffic noises were combined using audio software.

An urban background noise was recorded early in the morning by Trollé *et al*. (3) without distinguishable noise events in order to be mixed to the combined noise sequences built for Exp. A.

2.1.2 Stimuli

The stimuli for combined road and tramway traffic noises were constructed according to Berglund and Nilsson's recommendations (10) and led to 25 combinations resulting from 5 different A-weighted sound pressure levels (denoted by SPL or L_{Aeq}) for road traffic noises and 5 different SPL for tramway traffic noises. The stimulus duration was 3 minutes.

For the construction of the road traffic noises, urban road vehicle pass-by noises from light vehicles, heavy vehicles, buses and powered-two-wheelers in different driving conditions (acceleration, deceleration and constant speed) were employed. Each of these pass-by noises exhibits SPL differences depending on the vehicle type and driving condition corresponding to SPL differences measured *in situ* (2). Urban road traffic scenarios considering peak and off-peak hours from recent traffic count data in French cities were considered: five road traffic noise sequences (RT1-RT5) with different traffic compositions and densities were constructed (Table 1). The SPL of the road traffic noise sequences ranged from 43 dB(A) to 53 dB(A).

Table 1 - The urban road traffic noise sequences and their SPL (L_{Aeq}), number of pass-bys, traffic compositions and traffic densities (peak and off-peak hours); LV: light vehicles, PTW: powered-two-wheelers, HV: heavy vehicles, B: buses.

Sequence	L_{Aeq}	Traffic	Nr of	Traffic composition			
	[dB(A)]	density	pass-bys	LV	PTW	HV	B
RT1	43	Off-peak	17	100 %			
RT2	46	Peak	34	100 %			
RT3	48	Off-peak	17	76 %	12 %	6 %	6 %
RT4	52	Peak	34	76 %	12 %	6 %	6 %
RT5	53	Peak	34	70 %	20 %	5 %	5 %

The tramway pass-by noises were different tramways in in-curve operating configurations which represent one of the worst exposure situations for residents living in the vicinity of tramway tracks. Three tramway pass-by noises (T1-T3) were selected based on the variation of SPL and an index reflecting the piercing character of squeal noise due to tonal components in high frequencies (TETC) (3). All the tramway pass-by noises used in the experiment contain squeal noise to a certain degree (the squeal noise of T1 is only just audible, it is moderate for T2 and the strongest for T3). Different scenarios of tramway traffic in French cities (peak and off-peak hours) were considered. The composition of the tramway traffic sequences is shown in Table 2.

Table 2 - The tramway noise sequences and their corresponding SPL (L_{Aeq}), traffic densities and number of pass-bys considering peak and off-peak hours of tramway traffic.

Sequence	L_{Aeq} [dB(A)]	Traffic density	Nr of pass-bys
T1	46	Off-peak	1
T2	48	Off-peak	1
2xT1	49	Peak	2
T3	50	Off-peak	1
2xT3	53	Peak	2

The urban background noise recorded by Trollé *et al*. (3) was equalized to 29 dB(A) and mixed to the sequences for the sound reproduction in a quiet room. The SPL of the 25 combined noise sequences measured at the ear position of the participants ranged from 45 dB(A) to 52 dB(A).

2.1.3 Participants

Thirty-eight participants performed this experiment (19 males, 19 females; mean age = 31 years; standard deviation = 11 years). They all declared normal hearing abilities and were paid for their participation.

2.1.4 Apparatus

The experiment took place in a quiet room with a background noise measured at 19 dB(A). The stimuli were reproduced employing a 2.1 audio system consisting of two active loudspeakers (Dynaudio Acoustics BM5A), one active subwoofer (Dynaudio Acoustics BM9S) and a high quality PC sound card (LynxTwo studio interface). The participants sat in front of the two loudspeakers such as the center of the listeners' interaural-axis and the loudspeakers formed an equilateral triangle. The loudspeakers were placed at a height of 1.20 m from the floor and the subwoofer was placed on the floor between the loudspeakers. The user interface was programmed using MATLAB.

2.1.5 Procedure

Prior to the experiment, participants were told they would listen to environmental sound sequences comprising urban background noise, road traffic noise and tramway noise. The participants were asked to imagine themselves "relaxing at home while reading". Newspapers and magazines were provided. After each stimulus, the participants were asked to first rate annoyance due to road traffic noise, then annoyance due to tramway noise and finally they were asked to rate annoyance due to the combination of the noises. The participants were asked to move a slider along a continuous scale ranging from "0" to "10", with 11 evenly spaced numerical labels and two verbal labels at both ends ("not at all annoying" and "extremely annoying"). The stimuli were played back in random order. The experiment lasted approximately 90 minutes.

2.2 Experiment B - Simulated context

Exp. B was carried out in an experimental living room simulating a real context of residents at home.

2.2.1 Stimuli

The stimuli duration was 6 minutes. To keep the total duration of the experiment within acceptable limits, the combined stimuli were limited to 4 road traffic noises combined with 4 tramway traffic noises of Exp. A. The 4 urban road traffic sequences were adapted to longer durations keeping the same traffic compositions relative to the total number of pass-bys. Tables 3 and 4 respectively summarize the composition of the urban road traffic noises and the composition of the tramway traffic noises used in Exp. B.

Table 3 - The road traffic noise sequences and their corresponding SPL (L_{Aeq}), traffic densities, number of pass-bys and traffic compositions considering peak and off-peak hours of traffic; LV: Light vehicles, PTW: powered-two-wheelers, HV: heavy vehicles, B: buses.

Sequence	L_{Aeq}	Traffic	Nr of	Traffic composition			
	[dB(A)]	density	pass-bys	LV	PTW	HV	B
RT1	48	Off-peak	34	100 %			
RT2	51	Peak	68	100 %			
RT3	53	Off-peak	34	76 %	12 %	6 %	6 %
RT4	58	Peak	68	70 %	20 %	5 %	5 %

Table 4 - The tramway noise sequences and their corresponding SPLs (L_{Aeq}), traffic densities and number of pass-bys considering peak and off-peak hours of tramway traffic.

Sequence	L_{Aeq} [dB(A)]	Traffic density	Nr of pass-bys
2xT1	51	Off-peak	2
2xT2	53	Off-peak	2
2xT3	55	Off-peak	2
4xT3	58	Peak	4

No artificial background noise was added to the sequences as the window of the experimental living room was partially open and the quiet local urban background noise was audible. The SPL was measured at 39 dB(A) in the living room. The SPL of the combined noise sequences ranged from 48 dB(A) to 57 dB(A). Thus, in total 16 stimuli (4 road traffic noises x 4 tramway noises) were used in this experiment.

2.2.2 Apparatus

The experiment was carried out in an experimental cottage on the campus of the ENTPE simulating a living room (11, 12). The living room was furnished with a couch, two chairs, a coffee table, a shelf and plants. The loudspeakers were placed outside the experimental living room and the window was slightly opened (12). From the inside of the living room through the window a garden with trees and a high hedge was visible. The experiment was controlled from a room situated next to the experimental room using a PC with a high quality sound card (LynxTwo studio interface). The stimuli were reproduced with a 2.1 audio system consisting of two active loudspeakers (Dynaudio Acoustics BM5A) and one active subwoofer (Dynaudio Acoustics BM9S). The two loudspeakers were placed at a height of 1.20 m in front of the façade and the subwoofer was placed on ground between the two loudspeakers. The loudspeakers were set up so that the center of the coffee table and the loudspeakers form an equilateral triangle. The loudspeakers were placed 5 m from each other and 3 m from the façade.

2.2.3 Participants

Exp. B was performed by 34 participants (16 female, 18 male; mean age = 33.2 years; standard deviation = 13 years). Up to five participants took part in the experiment simultaneously. All participants declared normal hearing abilities and were paid for their participation.

2.2.4 Procedure

First, the participants were introduced to the experiment and asked to imagine themselves at home in their living room with an open window, relaxing and performing a reading activity. Newspapers and magazines were provided. The participants were told that they would be in the presence of environmental sound sequences comprising road traffic noise and tramway noise. Furthermore, they were advised not to talk during the experiment and not to close the window. Printed rating scales were handed out to each participant after each stimulus reproduced in random order. The order of rating scales was consistent with Exp. A: First, participants were asked to rate partial annoyance due to road traffic noise, the partial annoyance due to tramway noise and finally total annoyance due to the combination of road traffic and tramway noises. The scales were the same as the ones used in Exp. A. The experiment lasted approximately 2 hours.

3. PREDICTION OF TOTAL ANNOYANCE FOR COMBINED URBAN ROAD AND TRAMWAY TRAFFIC NOISES

Different relevant total annoyance models from literature (*e.g*. 12) were tested to predict total annoyance due to combined road traffic and tramway traffic noises. Models of total annoyance are i) psychophysical when the independent variables are based on SPL or ii) perceptual when the independent variables are partial annoyance responses. The total annoyance models were constructed using data from Exp. A. The built total annoyance models were tested using data obtained in Exp. B.

3.1 Construction of total annoyance models

3.1.1 Calculation of partial annoyances for perceptual total annoyance models

Perceptual total annoyance models are usually calculated using measured partial annoyance responses. In this study, they were constructed using calculated partial annoyance responses based on indices from literature in order to investigate the relevance of such practical approach. Prior to the prediction of total annoyance due to a combination of noises using perceptual models, partial annoyance due to each noise must be calculated. In order to take into account different influential acoustical features of urban road traffic noises and of tramway traffic noises, partial annoyances were calculated based on indicators established in single noise exposure experiments (2-4). This approach has one main underlying assumption: partial annoyance is approximated by specific annoyance as it is considered in different studies dealing with combined noise exposure (13, 14).

For the calculation of partial annoyance due to urban road traffic noises the indicator proposed by Klein *et al*. (2) for the assessment of annoyance due to urban road vehicle pass-by noises was used on the basis of the results of Gille *et al*. (15): Road traffic noise annoyance is conditioned by the “worst” event within the noise sequence. The indicator (2) used for calculating the urban road traffic partial annoyance (A_{RT}) is:

$$A_{RT} = 0.50 * N_{mean} + 2.85 * m_{sputt,10} + 3.51 * m_{nas,10} + 0.026 * TETC_{16-24} - 0.79 \quad (1)$$

where N_{mean} represents mean loudness, $m_{sputt,10}$ and $m_{nas,10}$ two indices accounting for modulation sensations and $TETC_{16-24}$, a spectral index accounting for the total energy of tonal components within critical bands from 16 to 24 barks. For the calculation of partial annoyance (A_{TT}) due to the tramway traffic noises, the annoyance indicator proposed by Trollé *et al*. (3, 4) for pass-by noises of tramways in different operating configurations was used. This indicator was found to explain short-term annoyance due to tramway pass-by noise in different operating configurations. The indicator was based on L_{Aeq} and TETC for tonal components within critical bands from 12 to 24 Bark (here denoted $TETC_{12-24}$):

$$A_{TT} = 0.158 * (L_{Aeq} - 46.1) + 0.148 * (TETC_{12-24} - 46.1) + 1.98 \quad (2)$$

In the following, these annoyance indicators will allow to calculate the partial annoyances used as independent variables to construct perceptual total annoyance models.

3.1.2 Construction of perceptual and psychophysical total annoyance models

Five relevant total annoyance models from literature were considered: 4 perceptual models (strongest component, vector summation, regression and mixed models, *e.g.* 12) and 1 psychophysical model (weighted summation model (13) which is the basis of the annoyance equivalents model (14)). Considering total annoyance models, the perceptual models are often found to perform better (*e.g.* 12). For the construction of the perceptual and psychophysical total annoyance models, the independent variables were considered using regression analysis. For the perceptual models, the independent variables were the road traffic and tramway traffic partial annoyances calculated from Eqs. 1 and 2, respectively. This has led to the proposition of a calculated form of the perceptual models whereas the classical form of these models is based on measured partial annoyances with the constraint to measure partial annoyances in order to predict total annoyance for field studies.

The total annoyance models were assessed based on the determination coefficient (R^2), the adjusted determination coefficient (R^2_{adj}) and the standard error of the estimate (SE). These parameters resulted from the regression analysis carried out between total annoyance responses collected during Exp. A, and the independent variables. The higher the R^2 and the R^2_{adj} and the lower the SE, the better is the goodness-of-fit of the total annoyance model.

The vector summation model was optimized with an angle $\alpha_{1,2}$ equal to 116.8° and the weighted summation with its parameter *k* equal to 15. The coefficients calculated for the mixed model were not significant. Hence, this model was excluded from the analysis. Table V presents the model fit of the models built using Exp. A.

Table 5 - Construction and comparison of the model fit of the selected total annoyance models. The model fit is represented by the determination coefficient R^2, the adjusted determination coefficient R^2_{adj} and the standard error SE.

Model	R^2	R^2_{adj}	SE
Strongest component	0.82	0.81	0.47
Vector summation	0.42	0.42	0.83
Regression	0.85	0.84	0.44
Weighted summation ($k = 15$)	0.30	/	2.54

The weighted summation model yields the smallest model fit compared to the other models. Among the perceptual models, the vector summation model presents the smallest model fit. Regarding the strongest component and the regression model their R^2 and SE are almost equal.

3.2 Testing of total annoyance models

The total annoyance models previously constructed were tested using annoyance data obtained in Exp. B. The prediction quality of the total annoyance models was assessed by comparing the Bravais-Pearson correlation coefficient (r), the slope and the intercept values resulting from the correlation and the regression analysis between the measured total annoyance responses from Exp. B and the predicted total annoyance responses obtained by applying the models constructed in the previous section. Table 6 shows the results of the model comparison in terms of prediction quality.

Table 6 - Comparison of the prediction quality of the calculated perceptual and the psychophysical total annoyance models. The correlation coefficient r and the regression line determined between the measured total annoyance from Exp. B and the predicted annoyance are provided. $^{a}p < 0.001$, $^{b}p < 0.05$.

		Regression line	
Model	r	Slope	Intercept
Strongest component	0.92^{a}	1.08	0.83
Vector summation	0.90^{a}	0.55	1.69
Regression	0.91^{a}	1.16	1.39
Weighted summation	0.55^{b}	0.25	6.41

The constructed total annoyance models strongly correlate with the measured total annoyance except the weighted summation model. The strongest component model yields the best results among the calculated perceptual models tested.

4. Discussion and conclusion

The urban road traffic and tramway traffic partial annoyance responses were predicted using combinations of indices established in single noise exposure experiments (2-4).

Such approach makes sense from a practical point of view. The issue in *in situ* measurement campaigns for combined noises is that combined noises mostly occur simultaneously, thus making it difficult to measure single noises in isolation. In such a case, it is necessary to characterize these noises in single noise exposure situations and apply this characterization to combined noises as done in previous studies (13-14).

The weighted summation model proposed by Vos (13) and its generalized form the annoyance equivalents model (14) are interesting models as they are based on simple energy-based indices. Recent field studies indicate that the annoyance equivalents model is not adapted to predict total annoyance (*e.g.* 1). The current study suggests that total annoyance prediction may be more accurate based on perceptual total annoyance models which involve the characterization of each noise source independently using indicators proposed for single noise exposure. This is congruent with other studies which showed that perceptual models predict total annoyance more adequately than psychophysical models for field and laboratory data (*e.g.* 12, 16-17). Among these models the strongest component model yielded the best results.

To predict total annoyance in field conditions, perceptual total annoyance models would require the collection of partial annoyance responses from residents (*e.g.* 16). From a practical perspective, it would be highly advantageous (less time consuming, cost effective) to predict total annoyance based on calculated partial annoyance responses. The perceptual total annoyance models tested in this work were based on partial annoyance responses calculated using indicators proposed in literature for specific annoyance. It was shown that partial annoyance due to urban road traffic noise could be calculated using the noise annoyance indicator proposed by Klein *et al.* (2). Partial annoyance due to tramway traffic noise could be characterized using a noise annoyance indicator proposed by Trollé *et al.* (3-4). Further studies need to be carried out in order to explore this interesting perspective.

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