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Estimation of psychoacoustic indices and annoying auditory sensations from sound pressure levels of urban road traffic

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ABSTRACT

The day-evening-night noise level (L_{DEN}) is often used as an index of noise annoyance. However, various other acoustical and psychoacoustical indices have been shown to improve noise annoyance models in comparison with models solely based on L_{DEN}. The difficulty is to determine such indices in the field, since that requires numerous in-field recordings and tedious calculations. Alternatively, it might be possible to infer such indices from the equivalent sound pressure level (L_{Aeq}) of the noise sources used in the production of European noise maps. In the current study, such alternative is assessed from a perceptual point of view. A listening test was carried out with 30 participants in order to assess annoying auditory sensations evoked by road traffic noise at different distances from the main street in urban environments. For each auditory sensation, i) the relationship between the calculated psychoacoustic index and the rated sensation magnitude, as well as ii) the relationship between the auditory sensation and the L_{Aeq} of the noise sample were determined. These two relationships permitted to reliably estimate psychoacoustic index values from the L_{Aeq} of the road traffic noise.

Keywords: psychoacoustic index, annoying auditory sensations, estimation of psychoacoustic indices from sound pressure level of sources

1. INTRODUCTION

In urban areas, noise annoyance is a major source of concern. Road traffic is the most annoying noise source (*e.g.* 1, 2). European cities of more than 100,000 inhabitants manage noise exposure using strategic noise maps (3). These maps are based on L_{DEN}, the day-evening-night level, and represent noise exposure to transportation noise sources. This index is also used in exposure-effect relationships to estimate the percentage of people annoyed by a transportation noise source (1). However, it does not cover some acoustical features known to be particularly annoying, *i.e.* spectral content, irregular amplitude variation or modulation (*e.g.* 4-7).

It is also well known that non-acoustical factors, such as noise sensitivity, influence noise annoyance (*e.g.* 8). Noise annoyance models, considering noise sensitivity and psychoacoustic indices characterizing different annoying acoustical features, have been proposed based on laboratory research (*e.g.* for road traffic noise (5), railway noise (6)). However, it might be difficult to apply such models to the field, since most psychoacoustical indices cannot be predicted or measured for a large number of urban locations.

To overcome this difficulty, a methodology was proposed to estimate psychoacoustic index values from the A-weighted equivalent sound pressure level (L_{Aeq}) or L_{DEN} of the noise sources (9). The estimation was numerically obtained from a set of sound recordings carried out in urban areas exposed to urban road traffic noise and aircraft noise. Based on recent psychoacoustic annoyance models and the estimation of psychoacoustic index values from the L_{DEN} specified in noise maps, noise annoyance ratings were predicted for two French cities (9). The comparison of the predicted annoyance ratings

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with annoyance ratings collected from a socio-acoustic survey showed an improvement of annoyance prediction due to the psychoacoustic index-based annoyance models in comparison with models solely based on L_{DEN}. In the current study, the estimation of psychoacoustic index values from the noise source L_{Aeq} is investigated from a perceptual point of view by investigating the variation of annoying auditory sensations as a function of the noise source L_{Aeq}. A listening test was carried out under laboratory conditions to assess sensations evoked by urban road traffic noise at different distances from the main street in urban environments. For each auditory sensation studied, i) the relationship between the rated auditory sensation magnitude and the L_{Aeq} of the noise sample, as well as ii) the relationship between the calculated psychoacoustic index and the rated sensation magnitude were determined. These two relationships permitted to estimate psychoacoustic index values from the L_{Aeq} of the urban road traffic noise.

2. THE EXPERIMENT

Different types of urban ground transportation noises were under consideration in the experiment: road traffic noises, powered-two-wheeler pass-by noises and railway pass-by noises. The experiment is presented in the following. First results related to urban road traffic noises will be presented in this paper.

2.1 Stimuli

The urban ground transportation noises were grouped into 3 series of stimuli.

For the series of railway noises, two train pass-by noises and two tramway pass-by noises, stereophonically recorded at 10 m from the tracks (6), were selected.

The series of powered-two-wheeler noises consisted of two motorcycles, one at constant speed, and one accelerating, stereophonically recorded at 3 m from the source (10).

For the series of urban road traffic noises, three traffic noise sequences were constructed by joining different single vehicle pass-by recordings, which stemmed from the perceptual typology of urban road vehicle pass-by noises proposed by Morel *et al*. (10). They were recorded at 3 m from the source. The three road traffic noise sequences included a light vehicle, a powered-two-wheeler and a heavy vehicle, in various orders and with various driving conditions.

Each recorded single pass-by was specifically selected for containing acoustical features related to annoying auditory sensations, such as high-frequency content for train pass-by noises (*e.g.* squealing noise (6)) or for road vehicle pass-by noises (*e.g.* breaking noise (7)) and strong modulation components for road vehicle pass-by noises (7).

The 3 urban road traffic noises and the 2 powered-two-wheeler noises were processed using a computer software to simulate sound propagation in an urban environment at distances of 10 m, 13 m, 18 m, 24 m, 32 m, 42 m, 56 m and 75 m, both for propagation in a U-shaped street and in an open street. The software used, Code_TYMPAN (11), and the corresponding simulation process had been selected and evaluated for this purpose from a perceptual point of view (12). The simulation process consisted of applying third-octave attenuations to the recordings to account for atmospheric absorption, reflections on the ground, and on nearby buildings of a U-shaped street. In the current study, the simple geometrical spreading was also considered: the sound pressure level logarithmically decreases with distance. For each series of urban road transportation noises, this led to the construction of 24 attenuation transfer functions (8 distances and 3 types of propagation (U-shaped street, open street, geometrical spreading)) to be applied to each initial sound recording.

For the series of urban road traffic noises, there were 75 stimuli (3 compositions x (8 distances x 3 propagation types + 1 initial sound recording)). Their equivalent sound pressure level ranged from 33.6 to 65.2 dB(A), with stimulus durations between 16 and 18 s.

The series of powered-two-wheelers was composed of 50 stimuli (2 motorcycles x (8 distances x 3 propagation types + 1 initial sound recording)). Their equivalent sound pressure level ranged from 38.3 to 66.2 dB(A) and their duration was comprised between 4 and 6 s.

For the urban railway noises (train or tramway), the initial sound recording distance was 10 m, so only 7 distances were simulated, from 13 to 75 meters, with the three different types of propagation (U-shaped street, open street, geometrical spreading). This led to a series of 88 railway stimuli (4 trains x (7 distances x 3 propagation types + 1 initial sound recording)). Their equivalent sound pressure levels ranged from 45.5 to 71.2 dB(A) and their duration from 8 to 17.6 s.

2.2 Apparatus

The experiment took place in a quiet room, with a background noise of 23.8 dB(A). The stereophonic stimuli were reproduced through a pair of active loudspeakers (Dynaudio BM5A) and one active subwoofer (Dynaudio BM9S). The loudspeakers were positioned at a height of 1.20 m, forming an equilateral triangle with the participant's interaural axis, according to Bech and Zacharov's (13) recommendations. The subwoofer was placed on the floor between both loudspeakers. The participants were facing a computer screen displaying the experimental interface. A computer was handling the interface and the reproduction of noises through a high-quality soundcard (LynxTwo studio interface). The reproduced stimuli were recorded at the participant's head position using both a Cortex Manikin MK2/NCF1 and an omnidirectional microphone in order to compute acoustical and psychoacoustical indices.

2.3 Participants

Thirty-two listeners took part in the experiment (15 men, 17 women, mean age: 33 years, SD: 11.1). They were paid for their participation, and they all declared normal hearing abilities.

2.4 Procedure

Stimuli were played back in random order. For each stimulus, the participants were asked to rate a number of auditory sensations related to different acoustical features.

For the urban railway noises, the acoustical features queried were i) high-pitched content (*e.g.* due to squealing noise (6)), ii) the presence of temporal amplitude variation, and iii) overall sound intensity.

For powered-two-wheelers, the acoustical features were i) high-frequency modulation (*e.g.* like the "buzzing of a wasp" for some scooter noises (7)) and ii) overall sound intensity.

For the urban road traffic noise series, the acoustical features were i) a high-pitched content (*e.g.* due to breaking noise (7)), ii) low-frequency modulation (*e.g.* in some accelerating vehicle noises (7)), iii) the presence of temporal amplitude variation, and iv) overall sound intensity.

A continuous scale ranging from 0 ("not present at all") to 10 ("extremely present") was used by the participants to rate these sensation magnitudes. Two preliminary phases allowed the participants to familiarize themselves with the task. For each series of stimuli, a practice phase allowed the participants to listen to reference transportation noises that were representative of each acoustical feature studied. A subsequent training phase then allowed the participants to rate the sensation magnitudes related to the acoustical features of a small number of stimuli, with the possibility to listen to them alternately with the reference transportation noises. The reference noises were not subsequently used in the experiment proper. Participants took breaks between each series of stimuli.

The experiment lasted 99 minutes on average (45 min for the railway noises, 15 min for the powered-two-wheeler noises, 39 min for road traffic noise).

3. RESULTS

3.1 Methodology for relationship determination

For each series of stimuli, and for the auditory sensation related to each acoustical feature, the analysis consisted of:

- Assessing the variation of the rated auditory sensation magnitude as a function of the A-weighted equivalent sound pressure L_{Aeq} of the source, and fitting a regression model. This expressed the rated sensation magnitude *Sensa* as a function *F* of the L_{Aeq} of the noise source:

$$Sensa=F(L_{Aeq}) \tag{1}$$

- Obtaining a relationship between the psychoacoustic index *Ind* calculated from the stimuli of the studied series and the corresponding rated sensation magnitude *Sensa*. This yielded the psychoacoustic index *Ind* as a function *G* of the rated sensation magnitude:

$$Ind=G(Sensa) \tag{2}$$

- Proposing a relationship between each psychoacoustic index and the L_{Aeq} of the noise source from the two previous relationships. This new relationship permits to estimate the psychoacoustic index values from the L_{Aeq} of the noise source. This estimated index value, denoted by *Est_Ind*, might be written as:

$$Est\_Ind = G[F(L_{Aeq})] \quad (3)$$

The goodness-of-fit of this last relationship was assessed by a correlation analysis between the estimated index values *Est-Ind* and the index values *Ind* calculated from the stimuli used in the experiment.

3.2 Urban road traffic noises: sensations related to high-pitched content, temporal amplitude variation and overall sound intensity

In this conference paper, results are presented for the series of urban road traffic noises, and 3 rated sensations related to high-pitched content, temporal amplitude variation and overall sound intensity. For conciseness, the sensation related to high-pitched content will be denoted by *high-pitched* and the sensation related to temporal amplitude variation will be denoted by *fluctuation*. Finally, the third sensation studied, related to sound intensity, is loudness.

Figure 1 displays an example of the variation of the rated high-pitched sensation magnitude as a function of the level of the urban road traffic noise L_{Aeq}. Due to the observed trend, a linear regression between this rated sensation magnitude and L_{Aeq} was computed.

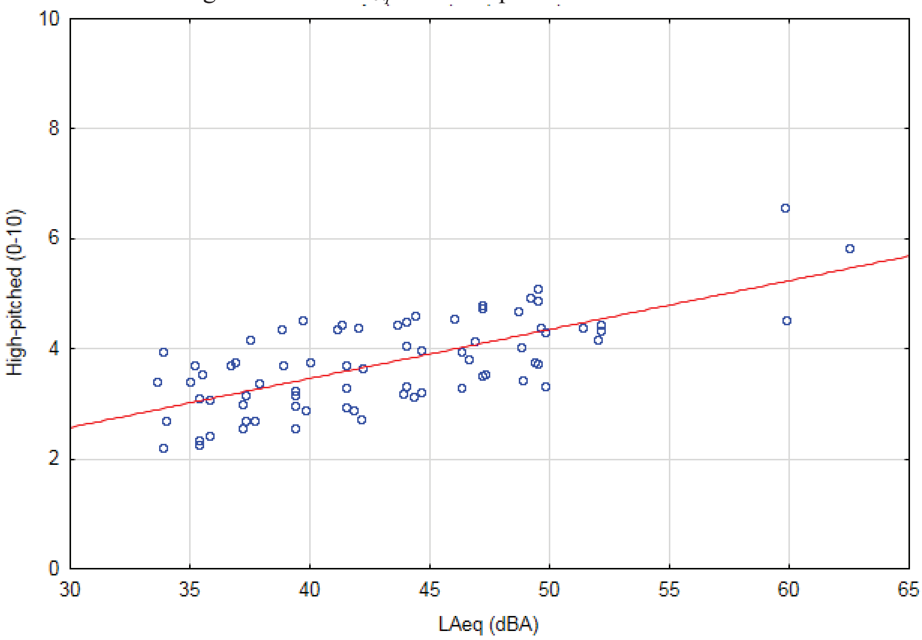

Figure 1 – Linear regression between high-pitched sensation magnitude (0-10) and L_{Aeq} (dBA)

Table 1 displays the regression equations obtained between the rated magnitudes of the three sensations and the level of the urban road traffic noise, L_{Aeq} (cf. Eq. (1)).

Table 1 – Relationships between rated sensation magnitudes and the urban road traffic A-weighted equivalent sound pressure level (L_{Aeq}). $Sensa_{Loudness}$: loudness; $Sensa_{High\text{-}pitched}$: sensation related to high-pitched content; $Sensa_{Fluctuation}$: sensation related to temporal amplitude variation.

Sensation	Equation of relationships
Loudness	$Sensa_{Loudness} = 0.270 \cdot 10^{0.0235 \cdot L_{Aeq}}$
High-pitched	$Sensa_{High-pitched} = 0.0888 \cdot L_{Aeq} - 0.897$
Fluctuation	$Sensa_{Fluctuation} = 0.760 \cdot 10^{0.014 \cdot L_{Aeq}}$

Table 2 shows the relationships between the psychoacoustical indices and the rated sensations (*cf.* Eq. (2)).

The first index is the loudness index *N*. The two other indices are $TETC_{16\text{-}24}$ and *σ'(N)* to respectively account for high-pitched content (7) and temporal amplitude variation (5) of urban road traffic noise. They are defined as follows

$$TETC_{16-24} = 10\, log_{10}\left(\int_{15}^{24} 10^{L(z)/10}\, dz\right) \tag{4}$$

TETC$_{16\text{-}24}$ corresponds to the Total Energy of Tonal Components between critical bands 16 and 24 Barks. The variable *L(z)* is the maximal level of the tonal components in a given critical band *z*.

$$\sigma'(N) = \sqrt{{}^{1}/_{T} \int_{0}^{T} \left({}^{dN}/_{dt}\right)^{2} dt} \tag{5}$$

σ'(N) stands for the temporal derivative of loudness *N*. Due to the mathematical expression, the index accounts for both regular and irregular amplitude variations.

Table 2 – Relationships between indices and the rated sensations. *N*: loudness index (sone); *TETC*$_{16\text{-}24}$: Total Energy of Tonal Components between critical bands 16 and 24 Barks (dB); *σ'(N)*: temporal derivative of loudness *N* (sone/s); $Sensa_{Loudness}$: loudness; $Sensa_{High\text{-}pitched}$: sensation related to high-pitched content; $Sensa_{Fluctuation}$: sensation related to temporal amplitude variation.

Index	Equation of relationships
N	$N = 0.676 \cdot Sensa_{Loudness} - 0.362$
TETC$_{16\text{-}24}$	$TETC_{16-24} = 18.9 \cdot Sensa_{High-pitched}{}^{0.737}$
σ'(N)	$\sigma'(N) = 2.29 \cdot Sensa_{Fluctuation}{}^{1.57}$

Finally, Table 3 presents the relationships obtained by applying Eq. (3) using both Eq. (1) and (2). For these final results, the quality of the fit is indicated by the correlation coefficient r between the index values estimated from the L_{Aeq} of the noise sources and the psychoacoustical index values calculated from the experimental stimuli directly.

Table 3 – Relationships between psychoacoustical indices and the A-weighted equivalent sound pressure level of the urban road traffic noise (L_{Aeq}). *N*: loudness index (sone); *TETC*$_{16\text{-}24}$: Total Energy of Tonal Components between critical bands 16 and 24 Barks (dB); *σ'(N)*: temporal derivative of loudness *N* (sone/s); r: the correlation coefficient between index values estimated from L_{Aeq} and index values calculated from the stimuli.

Index	Equation of relationships	r
N	$N = 0.676 \cdot (0.270 \cdot 10^{0.0235 \cdot L_{Aeq}}) - 0.362$	0.99
TETC$_{16\text{-}24}$	$TETC_{16-24} = 18.9 \cdot (0.0888 \cdot L_{Aeq} - 0.897)^{0.737}$	0.87
σ'(N)	$\sigma'(N) = 2.29 \cdot (0.760 \cdot 10^{0.014 \cdot L_{Aeq}})^{1.57}$	0.99

3.3 Comparison between the rated sensation magnitude and the corresponding index value

In the present paper, we restrict ourselves to performing this comparison for overall loudness. Figure 2 presents the loudness index estimated from L_{Aeq} versus the loudness rating obtained in the listening test. The significant correlation coefficient between the two sets of data is equal to 0.85.

If one considers the correlation coefficient between the loudness index *N* calculated from the stimuli and the loudness rating obtained in the listening test, a similar correlation is obtained and equal to 0.84 (*cf.* figure 3).

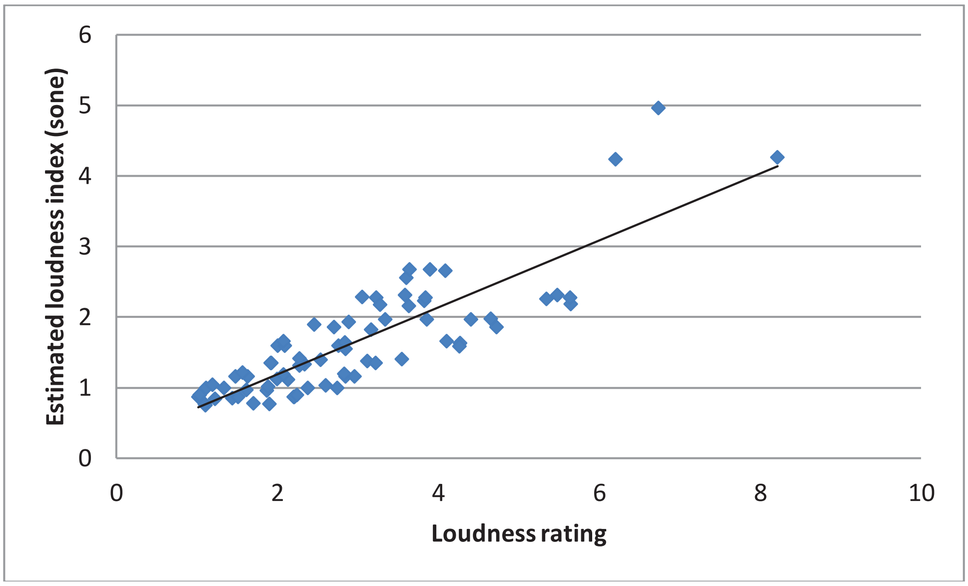

Figure 2 – Comparison between the loudness index estimated from the L_{Aeq} of the stimuli and the rated loudness magnitude (r=0.85; p<0.05)

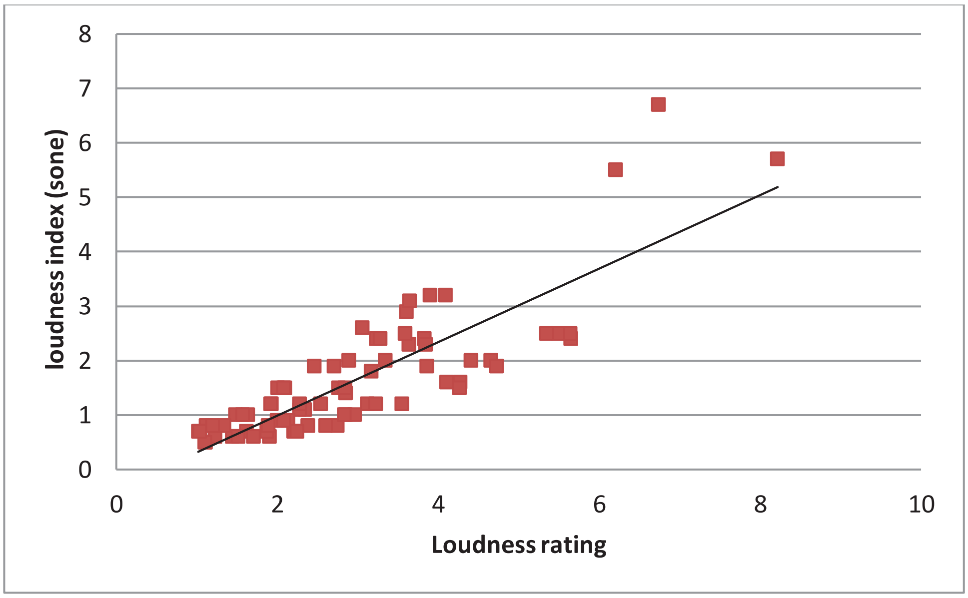

Figure 3 – Comparison between the loudness index N and the rated loudness magnitude (r=0.84; p<0.05)

These relationships underscore the validity of estimating the loudness index from the A-weighted sound pressure level of the urban road traffic noise excerpts.

In reference (9), it was proposed to estimate loudness index values from the L_{Aeq} of urban road traffic noise. The determination was carried out numerically from urban road traffic noise excerpts recorded in field.

Using data of the current experiment, it was possible to assess this numerical determination from a perceptual point of view. For doing this, the relationship from (9) was used to estimate loudness index values from the L_{Aeq} of the experimental stimuli. Then a comparison was carried out between the thus estimated loudness index values and the loudness ratings gathered during the current experiment (see Figure 4).

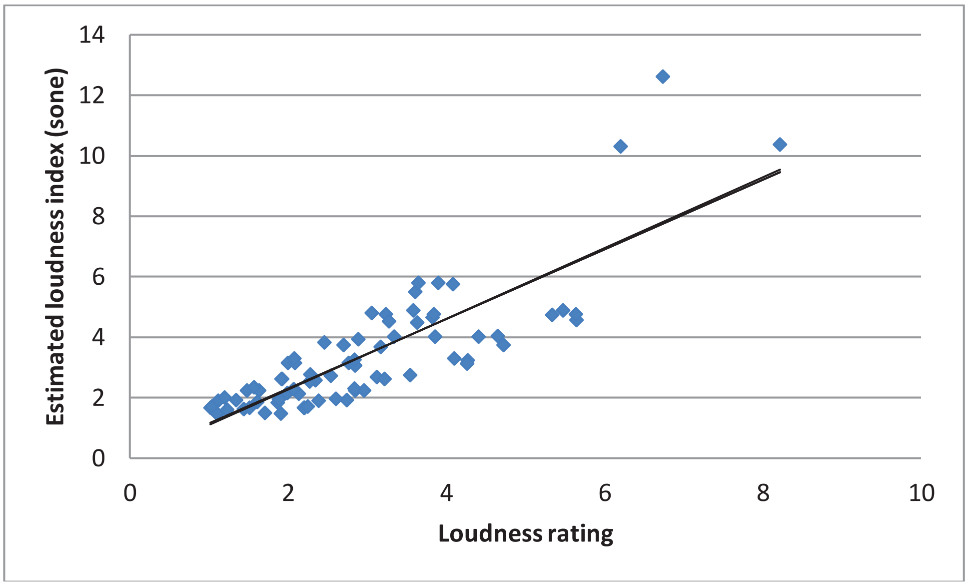

Figure 4 - Comparison between the estimated loudness index [based on (9)] and the loudness ratings ($r=0.84$; $p<0.05$)

This yielded a moderately high and significant correlation coefficient amounting 0.84. It indicates that the numerical methodology proposed in (9) to estimate loudness index values from the L_{Aeq} of urban road traffic noise seems to be valid from a perceptual point of view and equivalent to the one determined in the current study based on a listening test.

DISCUSSION AND CONCLUSIONS

Studies carried out in field highlighted the need for additional acoustical indices to better characterize annoyance, and in particular the use of psychoacoustic indices (*e.g.* (14-15)). But many psychoacoustic indices cannot be predicted or measured in a large urban environment. From excerpts of urban road traffic noise and of aircraft noise, a methodology (9) was proposed to estimate psychoacoustic index values from the equivalent sound pressure level, or L_{DEN}, of the noise sources. The methodology led to estimated values which allowed enhancement of annoyance prediction from models using psychoacoustic index values in comparison with models solely based on L_{DEN}. The current study proposed to estimate such index values from a perceptual point of view. This was accomplished by carrying out listening tests using different urban ground transportation noises (powered-two-wheeler noises, road traffic noises and railway noises). First results obtained for three auditory sensations evoked by urban road traffic noises indicate that the perceptual methodology to estimate different psychoacoustic index values from the sound pressure level of the sources seems to be a valid approach, since it yielded strong relationships 1) between the thus estimated index values and the index values calculated from the stimuli, and 2) between the estimated index values and the sensation magnitude ratings. More specifically, a comparison between the estimated loudness values obtained from the methodology proposed in (9) and the loudness ratings gathered during the current experiment resulted in a strong correlation and thus indicates the perceptual relevance of the numerical methodology proposed in (9) to estimate loudness indices from in-field sound pressure levels of urban road traffic noises.

The current study presented first results. These results indicated the perceptual relevance of the estimation of psychoacoustic index values from sound pressure levels of the sources. A further research perspective might be to investigate the estimation of psychoacoustic indices using various in-field recordings accounting for different transportation noise situations.

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