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Int. J. Hyg. Environ.-Health ▮ (▮▮▮▮) ▮▮▮–▮▮▮

International Journal of Hygiene and Environmental Health

www.elsevier.de/ijheh

Personal noise ranking of road traffic: Subjective estimation versus physiological parameters under laboratory conditions

Reinhard B. Raggam[a], Michael Cik[b,c], Robert R. Höldrich[c], Kurt Fallast[b], Eugen Gallasch[d], Martin Fend[d], Andreas Lackner[e], Egon Marth[a,*]

[a]*Institute of Hygiene, Department of Environmental Medicine, Medical University of Graz, Austria*
[b]*Institute of Highway Engineering and Transportation Planning, Graz University of Technology, Graz, Austria*
[c]*Institute of Electronic Music and Acoustics, University of Music and Dramatic Arts, Graz, Austria*
[d]*Institute of System Physiology, Medical University of Graz, Austria*
[e]*Department of Neurotology, ENT Clinic, Medical University of Graz, Austria*

Received 24 February 2006; received in revised form 17 August 2006; accepted 21 August 2006

Abstract

Objective: To evaluate the subjective estimation of noise-induced discomfort and its correlation to psychoacoustic and physiological parameters under laboratory conditions. To establish an effective description of sound qualities of road traffic noise, supplementing the current standards and calculation specifications.

Methods: Pass-by vehicle noise samples were binaurally recorded with a dummy head measurement system, and synthetically composed to six vehicle ensembles considering different road beds, varying speed profiles and noise barriers. Fifty-one persons were selected and tested under laboratory conditions. Study participants were exposed to defined acoustic stimuli, alternating with neutral phases lacking acoustic content in a listening room. Concomitant recording of electrocardiogram (ECG) and respiratory rate was performed. Subjective estimation of noise-induced discomfort of assigned vehicle ensembles was rated on a personal ranking scale (PRS) by the study subjects. Subjective ratings were combined with objective psychoacoustic parameters by multiple regression analysis.

Results: Heart rate was increased during all noise exposure phases compared to neutral phases; the increase of heart rate differed among vehicle ensembles and was statistically significant in two cases ($p<0.01$). Respiratory rate remained unaffected. Personal rankings also differed among vehicle ensembles and correlated well with objective psychoacoustic parameters ($p<0.0001$); e.g., loudness combined with roughness describes the correlation with subjective estimation of noise-induced discomfort better than the A-weighted sound level. Vehicle ensembles rated more unpleasant caused higher increases in heart rate as well ($p<0.0001$).

Conclusions: The sound quality of road traffic noise as it is described by various psychoacoustic parameters not only determines the subjective estimation of noise-induced discomfort but in addition affects physiological parameters like heart rate. This should be considered for future perspectives in road- and traffic planning and therefore may serve construction engineers as well as traffic planner as a supplemental tool.

Keywords: Road traffic noise; Psychoacoustic and physiological parameters; Laboratory attempt conditions; Subjective estimation; Personal ranking scale

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[*]Corresponding author. Tel.: +43 316 380 4360; fax: +43 316 380 9648.
E-mail address: egon.marth@meduni-graz.at (E. Marth).

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doi:10.1016/j.ijheh.2006.08.007

Please cite this article as: Raggam, R.B., et al., Personal noise ranking of road traffic: Subjective estimation versus physiological parameters under laboratory.... Int. J. Hyg. Environ.-Health (2006), doi:10.1016/j.ijheh.2006.08.007

Introduction

In a time of intensified efforts towards environmental protection, especially the protection from "unwanted sounds" has become crucial. Not only the avoidance of hearing damage, which only occurs during high sound levels or long persisting acoustic irradiation, but also the impairment of the human well-being for instance caused by road traffic noise has to be considered. Road traffic noise, which is steadily increasing, is regarded as an important environmental health problem, the role of road traffic noise as stressor has also been brought up and was extensively investigated (Babisch et al., 2005; Babisch, 2002, 2005; Bluhm et al., 2004; Griefahn et al., 2000; Jarup et al., 2005; Ouis, 2002). Moreover, disturbances of intended daily-live activities such as communicating, concentrated working, relaxing and sleeping occur even at low noise levels (Griefahn, 2002; Maschke et al., 2004; Ouis, 1999). This results in sustaining noise-induced discomfort, and in the long run may lead to further severe health effects like cardiovascular disease and an increased myocardial infarction risk (Babisch et al., 2005; Babisch, 2000; Ising et al., 1999).

The subjective estimation of noise-induced discomfort can be predicted only with difficulty in general (Morgan and Dirks, 1974). The informational quality of a certain sound like semantic or pragmatic aspects plus the intentional attitude of a person are highly situation-specific and therefore cannot be modelled in a reliable way. Thereby, fuzzy mathematical soft-computing methods describing the relationship between noise-induced discomfort and objective noise parameters are important to consider as reported previously (Botteldooren and Lercher, 2004).

Noise, once recognized by the human hearing, causes certain reactions. These reactions depend on signal characteristics like sound pressure level, frequency spectrum, stationary conditions and duration (Hellbrück et al., 2001; Moore, 1996). They also depend on physical and psychological conditions as well as on the current activity of the individual (Babisch et al., 2003). For the classification of sounds, independent perceptual base items such as loudness, roughness, sharpness, tonality and fluctuation strength are used by the human auditory system (Zwicker and Fastl, 1990). Modelling and combining these psychoacoustic parameters lead to an objective sound quality and are uninfluenced by the individual (Widmann, 1992; Zwicker, 1991). This can be tested under laboratory conditions if study participants are not able to allocate the presented acoustic source and in addition the sounds are lacking information content. The noise-induced discomfort is finally caused exclusively by the presented sound signal, the test subjects participate thereby under strict defined attempt conditions.

Therefore, an effective description of noise-induced discomfort can only be achieved by considering the characteristics of the human hearing including emotional aspects. At present, according to the current standards and calculation specifications, the impact of road traffic noise is represented by the A-weighted equivalent mean average sound level ($L_{\mathrm{A,eq}}$). In our opinion, this dimension considers too little the subjective estimation and evaluation of sound events by the affected and thus needs to be adjusted.

The study presented here was a co-project between the Institute of Highway Engineering and Transportation Planning, Graz University of Technology, the Institute for Electronic Music and Acoustics, University of Music and Dramatic Arts Graz, the Institute of Hygiene, the Institute of System Physiology and the Neurotology Department, ENT Clinic, Medical University Graz.

Methods and study design

Setup of the study

In a first step, different roadbeds which are most commonly found on Austrian highways were determined and selected for sound recordings (data source kindly provided by ASFINAG, the Austrian Highway Financing Company). Out of these various roadbeds, three different types were chosen: concrete (C), asphalt-concrete (AC) and split-mastix-asphalt (SMA). The pass-by noise of different passenger cars and motor trucks with variable speed profiles on each of these roadbeds were binaurally recorded with a dummy head measurement system HMS II (HEAD acoustics GmbH, Herzogenrath, Germany). Recordings were accomplished on 600 m long homogeneous road sections (RVS 3.02, Austrian Guidelines for roads and traffic) with free sound propagation within 100 m distance. Speed measurement of each passing passenger car and motor truck was also done. In order to keep the meteorological bias as small as possible, all measurements were performed between 2 and 4 o'clock in the night at same temperature, approximately stable humidity and zero wind.

In a second step, single vehicle recordings were synthetically composed to ensembles by audio software (Adobe Audition 1.5). Out of these composed vehicle ensembles, five defined samples were created (Fig. 1), simulating an averaged traffic-emerge on Austria's highways for a representative time period of 1 h during the night. The designed vehicle ensembles contained A-weighted sound levels from a minimum of 50 dB to a maximum sound level of 70 dB and typical A-weighted frequency spectra meeting the national standards of traffic noise frequencies (ÖNORM EN 1793-3: 1998 03 01: N).

To transfer the laboratory hearing attempt consisting of free field in situ recordings into laboratory conditions, a reference listening room meeting the reverberation

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Time	Alternating stimuli and neutral phases
180 sec	**Neutral phase A**
180 sec	**Vehicle ensemble A** ▪ 30 cars with 130 km/h ▪ 6 trucks with 90 km/h ▪ **SMA** (Highway A2 – km 141)
180 sec	**Neutral phase B**
180 sec	**Vehicle ensemble B** ▪ 30cars with 130 km/h ▪ 6 trucks with 90 km/h ▪ **Concrete** (Highway A9 – km 213)
180 sec	**Neutral phase C**
180 sec	**Vehicle ensemble C** ▪ 30 cars with 130 km/h ▪ 6 trucks with 90 km/h ▪ **SMA with noise barrier** (Highway A2 – km 145)
180 sec	**Neutral phase D**
180 sec	**Vehicle ensemble D** ▪ 30 cars with 130 km/h ▪ 6 trucks with 90 km/h ▪ **Asphalt-Concrete** (Highway S36 – km 5)
180 sec	**Neutral phase E**
180 sec	**Vehicle ensemble E** ▪ 30 cars with 80 km/h ▪ 6 trucks with 60 km/h ▪ **SMA** (Highway A2 – km 141)
180 sec	**Neutral phase A RP**
180 sec	**Vehicle ensemble A RP** reproducibility ▪ 30 cars with 130 km/h ▪ 6 trucks with 90 km/h ▪ **SMA** (Highway A2 – km 141)
180 sec	**Neutral phase end of attempt**

Fig. 1. Scheme of the composed vehicle ensembles and consecutive sequences presented during the laboratory hearing attempt showing alternating acoustic stimuli phases (vehicle ensembles) and neutral phases lacking acoustic content.

time and the background noise guidelines of the European Broadcasting union (EBU Tech. 3276 – 2nd edition, 5/1998) and the International Telecommunication Union (ITU-R BS. 775 and ITU-R BS. 16-1) was required. For that reason, the specially adapted psychoacoustics laboratory of the Institute of Highway

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Engineering and Transportation Planning, Graz University of Technology, was used.

Study participants and selection criteria

For the laboratory attempt, 51 healthy study participants with no record of cardiovascular abnormalities and no other chronic disease were selected including 28 females and 23 males between 19 and 50 years of age. The study was approved by the local ethic committee, Medical University of Graz, Austria; all study participants gave informed and written consent. To exclude prior existing deficiency in hearing, test subjects underwent audiometry. Afterwards, a standardized questionnaire reflecting the study participant's subjective estimation of being disturbed by road traffic noise by day and night time was applied. Additionally, the questionnaire checked for impairments of activities like communicating, working, and reading, concentrating, relaxing and sleeping in their residential area.

Assessment of physiological parameters

For assessing physiological parameters including heart rate and respiratory rate, three electrodes for ECG and an electronic impedance respiratory belt were attached on the thoracic wall of each test subject. The gained ECG and respiratory curves were monitored and recorded throughout the whole laboratory attempt by the g®MOBIlab (g-tec, GUGER TECHNOLOGIES, Graz, Austria). Evaluation and analysis of the collected data were performed with g®DAQsys 3.0 data acquisition system and g®BSanalyze 3.0 bio signal analysis (g-tec, GUGER TECHNOLOGIES).

Statistical analysis

Statistics were calculated with SPSS 13.0 software, $p<0.05$ was considered statistically significant. Multiple comparisons between subjective and objective parameters were done by means of multifactor ANOVA. Correlation analysis between defined vehicle ensembles and heart rate was calculated with Spearman's rank test.

Study design

The study design of the laboratory attempt was split into two sessions. In the first session, the study subjects were exposed to acoustic irradiation (as it is demonstrated in Fig. 1) in the listening room, concomitant physiological parameter recording. The acoustic irradiation consisted out of six defined vehicle ensemble samples – including one reproducibility sample – containing the features of different road beds, with varying speed profiles and noise barriers in a consecutive fashion. Vehicle ensembles alternated with neutral phases without any acoustic stimulus. The time-period of each vehicle sample and neutral phase was set to be three minutes; the whole laboratory attempt was terminated after thirty-nine minutes. In the second session, test subjects were subsequently asked to scale the aforementioned defined vehicle ensembles regarding subjective noise-induced discomfort on a personal ranking scale (PRS) in the listening room. Therefore, a software-related experimental assembly of the defined vehicle ensembles was developed and displayed on a monitor in front of the test subject. The attempt person could activate the noise samples by clicking the assigned start-symbol at the monitor. In that way, the attempt person had the possibility of comparing the vehicle ensembles to each other, if necessary, several times and finally judging subjective noise-induced discomfort by clicking a marker on the PRS. These judgements could be changed at any time within the evaluation. The PRS was assigned as an 11-graded interval scale, ranges were defined from "less unpleasant" to "very unpleasant" (Fig. 2). Furthermore, the attempt person was advised not to judge exclusively the different loudness of the noise contained in the individual samples, but also its sound characteristics.

Data processing

As a final step, the defined vehicle ensembles were processed with the Psychoacoustics Module of the ArtemiS Analyses System (HEAD acoustics GmbH). The psychoacoustic parameters loudness, roughness, sharpness, sound level, tonality and fluctuation strength were chosen for calculation. Results obtained from the subjective personal rankings of noise-induced discomfort were combined with the objective psychoacoustic parameters by multiple regression analysis and displayed in percentiles.

Results

To select a homogenous and healthy study collective, prior existing hearing damages had to be ruled out. Answering of an elementary standardized questionnaire by the study subjects was also obligatory. All 51 study subjects included in this study were tested by audiometry and showed normal audiograms (data not shown). The standardized questionnaire employed herein reflected on the one hand the study participant's subjective estimation of being disturbed by road traffic noise by day and night time, on the other hand, it checked for impairments of intended activities. Data are summarized in Fig. 3.

In the listening room, test subjects were exposed to acoustical irradiation under strict defined attempt conditions. The defined vehicle ensembles were acted

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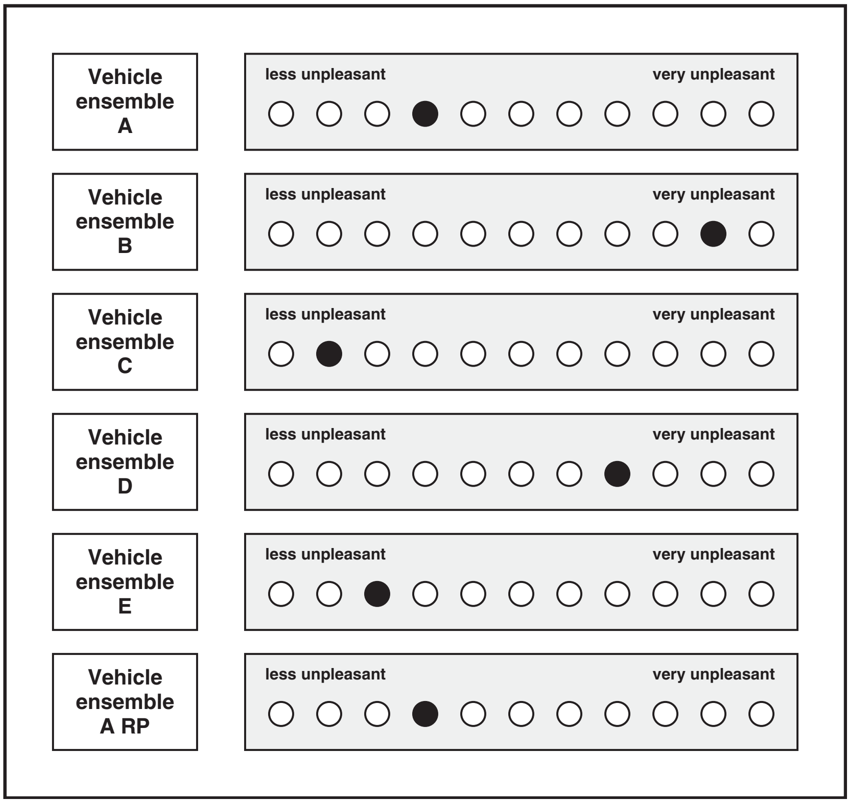

Vehicle ensemble A: ○ ○ ○ ● ○ ○ ○ ○ ○ ○ ○

Vehicle ensemble B: ○ ○ ○ ○ ○ ○ ○ ○ ○ ● ○

Vehicle ensemble C: ○ ● ○ ○ ○ ○ ○ ○ ○ ○ ○

Vehicle ensemble D: ○ ○ ○ ○ ○ ○ ○ ● ○ ○ ○

Vehicle ensemble E: ○ ○ ● ○ ○ ○ ○ ○ ○ ○ ○

Vehicle ensemble A RP: ○ ○ ○ ● ○ ○ ○ ○ ○ ○ ○

Fig. 2. Software-related experimental assembly of the defined vehicle ensembles as it was displayed on a monitor in front of the test subject. The attempt person judged the noise-induced discomfort by clicking a marker on the personal ranking scale (PRS). The PRS was assigned as an 11-graded interval scale, ranges were defined from "less unpleasant" to "very unpleasant".

out with alternating neutral phases (Fig. 1). Physiological parameters including heart rate and respiratory rate were concomitantly recorded and analysed. The heart rate was increased during all noise exposure phases compared to the alternating neutral phases which were lacking acoustic stimuli. Increase in heart rate differed among vehicle ensembles and was only statistically significant during vehicle ensemble B and D ($p < 0.01$), but not significant during the other vehicle ensembles (Fig. 4). Respiratory rate remained unaffected throughout the whole laboratory attempt (data not shown).

Evaluation of subjective personal rankings of noise-induced discomfort also differed among vehicle ensembles whereas ensembles B and D were rated significantly more unpleasant ($p < 0.001$) than the other vehicle ensembles (Fig. 5). Results obtained from the subjective personal rankings of noise-induced discomfort were combined with the objective psychoacoustic parameters by multiple linear regression analysis. Linear regression: loudness ($r = 0.825$), roughness ($r = 0.787$) and sound level ($r = 0.792$) correlated significantly ($p < 0.0001$) with noise-induced discomfort. Sharpness also correlated very well ($p < 0.001$) (Fig. 6a–d); the psychoacoustic parameters tonality and fluctuation strength had no influence in noise-induced discomfort. Multiple linear regression: loudness combined with roughness ($r = 0.842$) correlated significantly ($p < 0.0001$) with noise-induced discomfort. The two vehicle ensembles rated significantly more unpleasant (B and D), also causing significantly higher increases in heart rate.

Discussion

Traffic noise, in particular road traffic noise represents one of the most interfering effects frequently mentioned in relationship with environmental stressors (Schreckenberg and Guski, 2005). At present, the impact of traffic noise is represented by the A-weighted equivalent mean average sound level ($L_{A,eq}$) only. However, loudness of a sound event is caused by complex reciprocal effects of frequency components and their temporal development, resulting in the fact that sounds with identical $L_{A,eq}$ can lead to different loudness estimation; sounds are further strongly depending upon stationary conditions, reflecting that the actual noise-induced discomfort of sound events is unsatisfactorily represented by the ($L_{A,eq}$). Taken this into consideration, the aim of this study was to establish laboratory attempt conditions to evaluate the subjective personal ranking of noise-induced discomfort of road

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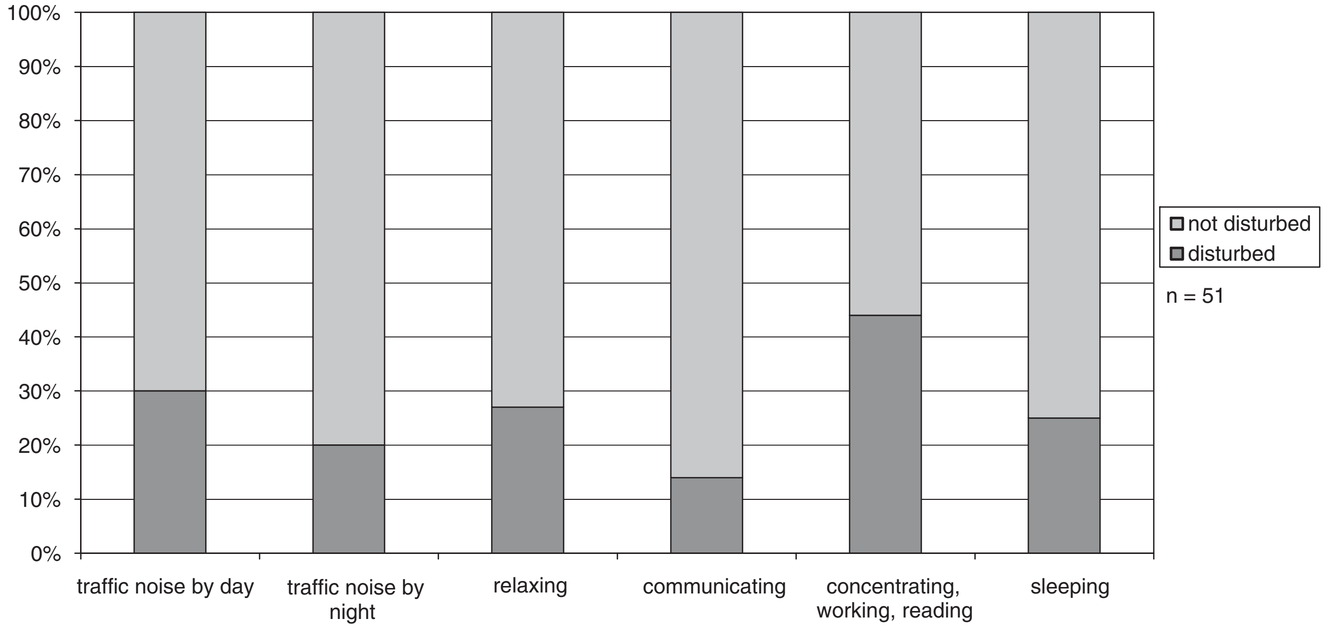

Fig. 3. Results taken from the elementary standardized questionnaire reflecting the study participant's subjective estimation of being disturbed by road traffic noise by day and night time; corresponding impairments of activities like communicating, working, and reading, concentrating, relaxing and sleeping in their residential area.

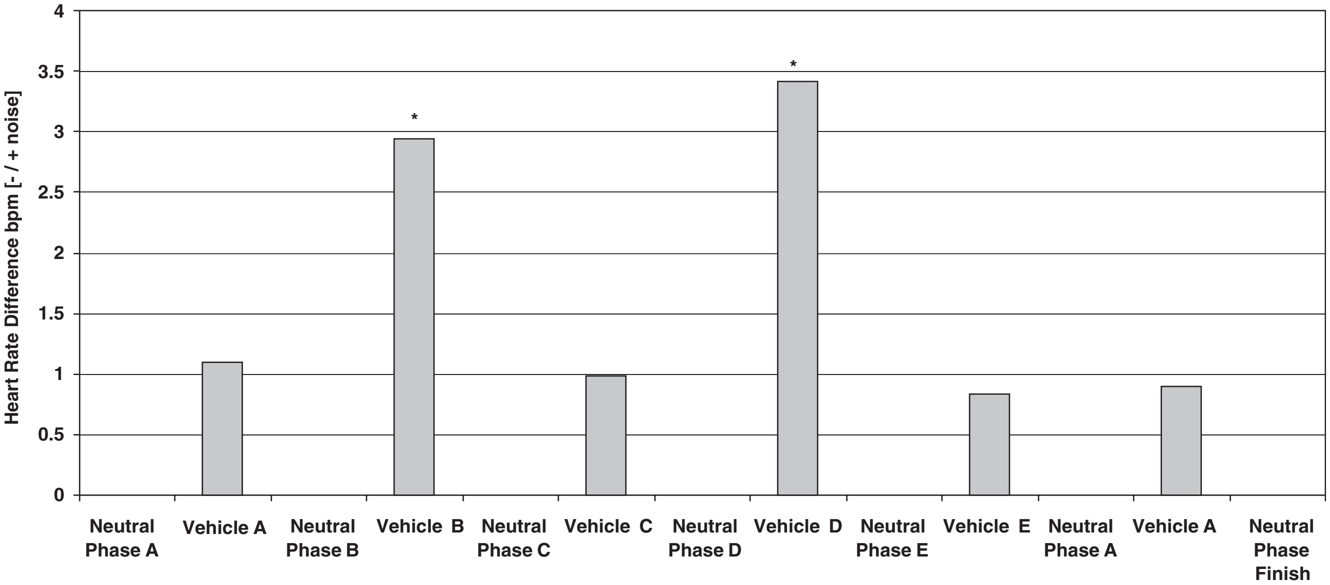

Fig. 4. Heart rate during all noise exposure phases compared to the alternating neutral phases. Increase in heart rate differed among vehicle ensembles and was statistically significant (*) during vehicle ensemble B and D ($p<0.01$). Vehicle ensembles A and A RP checked for reproducibility of the laboratory attempt.

traffic noise in combination with stress assessment. There are major advantages of such laboratory attempt conditions in comparison to free field in situ studies; homogeneous sound events are accurately reproducible, can variously be analysed and – most important – the study subject is not provoked by optical influences.

To gain an adequate noise database, road traffic was binaurally recorded with a dummy head measurement system representing cars and trucks passing-by on three different roadbeds with varying speed profiles and noise barriers. These recordings were composed to defined vehicle ensembles simulating an averaged traffic emerge on Austria's highways representing a time period of 1 h during the night. In order to verify the sound rendition, comparative presentation-listening tests in the CUBE (24-channel system for immersive 3D-sound-rendering)

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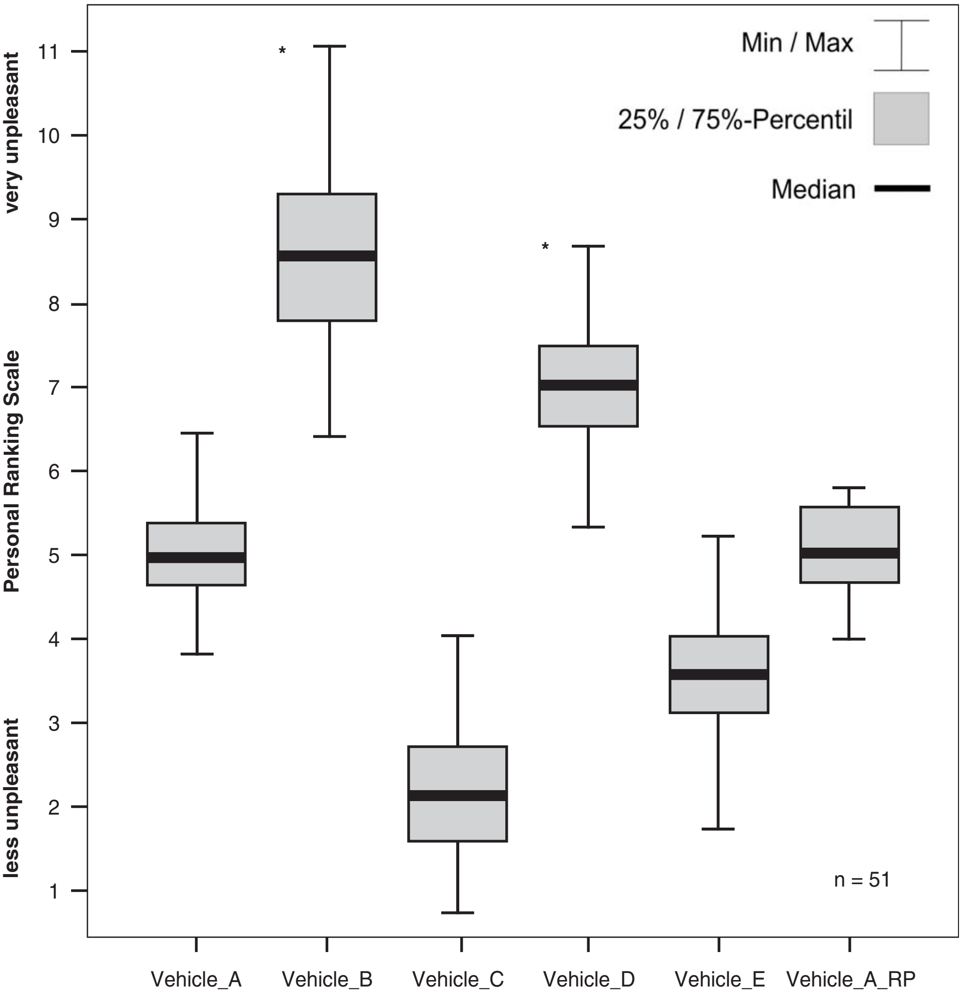

Fig. 5. Evaluation of subjective PRS, regarding noise-induced discomfort: results expressed in Box–Whisker–Blots. There were obvious differences in estimating noise-induced discomfort among the presented vehicle ensembles. Vehicle ensemble B and D were significantly regarded more unpleasant ($p<0.001$) compared to others. Vehicle ensembles A and A RP were rated equally, indicating high reproducibility.

at the institute of electronic music and acoustics were executed. We selected a homogenous healthy study collective and exposed them to these defined vehicle ensembles with alternating neutral phases in the acoustic laboratory, simultaneously ECG and respiratory rate were recorded. Study subjects also rated the perceptive noise-induced discomfort of each ensemble on an 11-graded interval scale, ranges were defined from "less unpleasant" to "very unpleasant". Therefore, comparative analysis of results obtained from subjective personal rankings of noise-induced discomfort with objective sound event parameters could be realized. This allowed reliable conclusion related to the variable effects of psychoacoustic parameters in creating noise-induced discomfort. By applying regression analyses, we examined in which way the single psychoacoustic parameters correlate with the evaluated discomfort. Out of these evaluations, particularly the large influence of loudness and roughness on the discomfort was to be emphasized. Furthermore, roadbeds and speed as well as adequate noise barriers had an influence on the subjective estimation of noise-induced discomfort.

When physiological parameters tested in this study were evaluated, it turned out that the heart rate was increased during all noise exposure phases (defined vehicle ensembles) compared to the alternating neutral phases which were lacking acoustic stimuli. This indicated a stress response as described elsewhere (Babisch et al., 2001; Ising et al., 1997). However, the increase in heart rate differed among the defined vehicle ensembles, only two were statistically significant elevated compared to neutral phases. Interestingly, the two vehicle ensembles causing significantly higher increases in heart rate were also rated significantly more unpleasant than the other vehicle ensembles. Respiratory rate remained unaffected throughout the whole laboratory attempt which may rely to low sound levels and short recording period.

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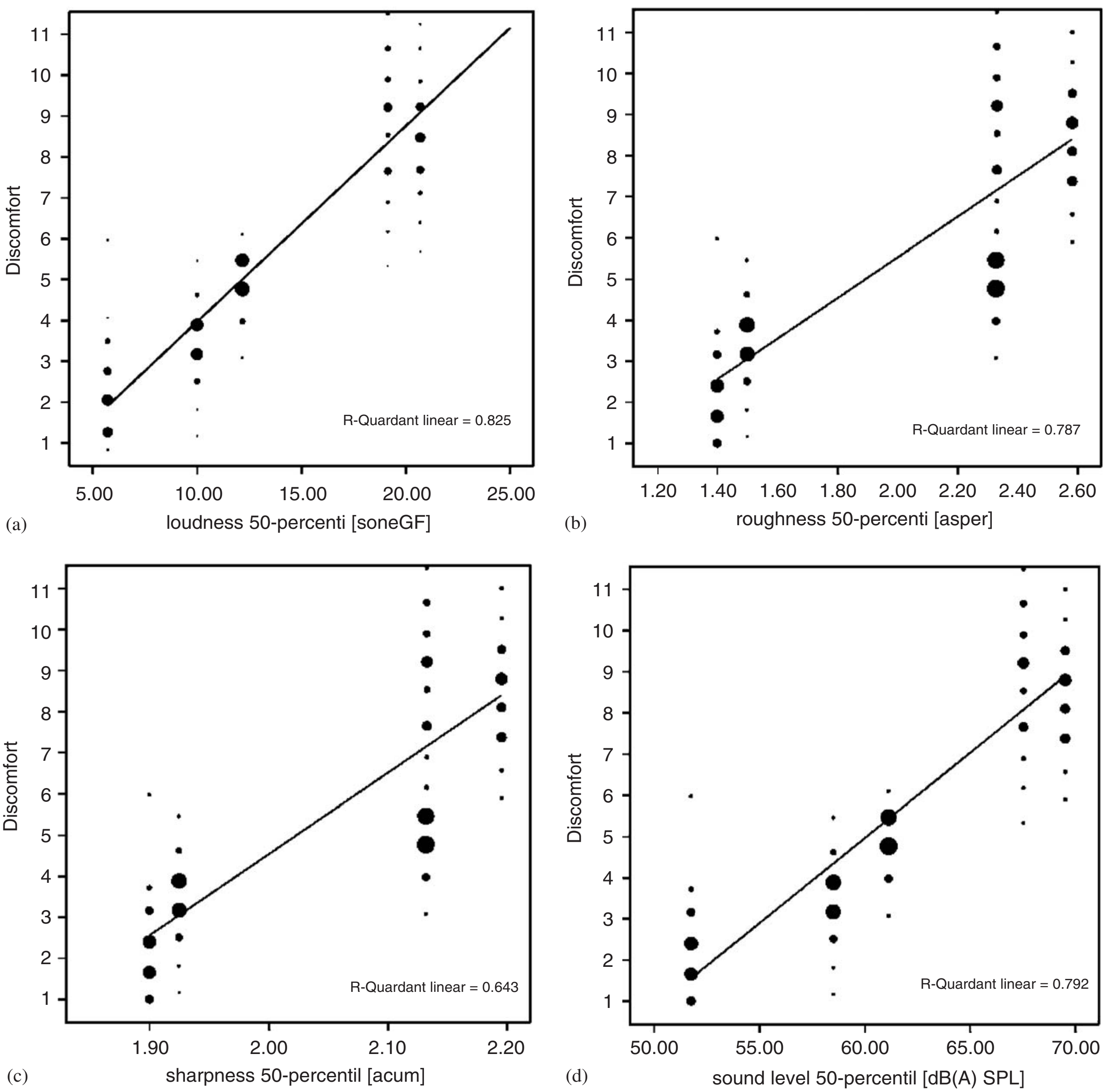

Fig. 6. Linear regression showing high correlation between subjective noise-induced discomfort and (a) loudness ($p<0.0001$), (b) roughness ($p<0.0001$), (c) sharpness ($p<0.001$) and (d) sound level ($p<0.0001$).

In conclusion, there is evidence of a high correlation between the degree of subjective estimation of noise-induced discomfort and single psychoacoustic parameters; loudness describes the correlation with noise-induced discomfort better than the A-weighted sound level given in dB. The physiological response of the human being to subjective noise-induced discomfort caused by road traffic noise resulted in an increase in heart rate as a direct response to a stressor and also correlated well. Future-orientated noise prevention needs more measures than lowering sound levels to a certain legal limit. It is crucially important to put the human being in the centre of interests and therefore take the influence of unpleasant sound sources – like motor, airstreams and rolling sounds of vehicles into consideration. Changes in roadbeds, tires, speed profiles and clever utilization of noise barriers can further reduce subjective noise-induced discomfort of road traffic noise.

The results presented in this study may serve as a supplemental tool for road- and traffic planners as well as construction engineers to predict not only objective consequences but also the subjective estimation of noise-induced discomfort caused by road traffic noise; more

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specific actions for a better controlling and regulation of road traffic noise emissions could be set in advance.

Acknowledgements

This multidisciplinary project was financed by ASFINAG, the Austrian Highway Financing and Operating Company, by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and the Austrian Federal Ministry of Transport, Innovation and Technology (BMVIT).

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