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Experimental Investigation of Noise Annoyance Caused by High-speed Trains

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Summary
A field experiment was conducted, to investigate the possible differences in perceived annoyance of noise caused by the traffic on a highway, by conventional trains and by high-speed trains, both conventional and magnetic levitation. The design of the experiment was different from earlier research in many ways. Most importantly, it was conducted in a realistic setting, a holiday cottage, and during the tests the participants were engaged in light daily activities. Traffic noise was reproduced in an ecologically valid way through loudspeakers placed outdoors. A stepwise selection of panelists was based on a screening questionnaire that was administered at the doorstep of 1500 persons living in the test site surroundings. The 100 panelists were selected to be representative of the Dutch population. The L_{Aeq}-annoyance relationships determined for the conventional high-speed train and for the magnetic levitation high-speed train did not differ significantly. The annoyance differences observed could be explained in terms of train noise differences in rise time and in propagation effects due to the distance between the track and the listening (recording) position.

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1. Introduction

A difference in perceived annoyance between train and other traffic noise at the same average sound level, has been observed in several field studies in the past [1, 2, 3]. In a number of countries, this observation has led to less restrictive regulation, or *railway bonus*, for train noise relative to noise from other sources such as highways, major roads or aircraft (usually 5 dB(A); see e.g. the German, French or Austrian legislation). With the introduction of high-speed trains and train-like transportation systems based on magnetic levitation (maglev), the question has arisen whether a difference in perceived annoyance of train and highway noise still exists. In particular, it is probable that spectral changes due to a higher fraction of aerodynamic noise and shorter rise times due to high speeds, would change the perception of high-speed train and maglev train noise.

The main goal of this research was to investigate the possible differences in annoyance, on the one hand, between magnetic levitation and conventional high speed trains and, on the other hand, between highway noise and train noise. Next to this, the influence of some additional factors on noise annoyance was studied, such as the distance between the source and the listener, the speed of the source and the rise time of the sound.

Prior laboratory research by Fastl and Gottschling [4] showed no significant difference in noise annoyance of a Transrapid 07 maglev train at a speed of 400 km/h and a conventional high-speed train at a speed of 250 km/h, if presented at a comparable A-weighted equivalent sound level. Conversely, Neugebauer and Ortscheid [5, 6] concluded that maglev noise annoyance differed markedly from that of a conventional train. An experiment by Vos [7, 8] showed that, if the outdoor ASEL (A-weighted Sound Exposure Level) was set equal, the Transrapid 08 maglev train was more annoying than a conventional intercity train, and approximately equally annoying as road traffic.

In addition to the fact that these previous studies were inconclusive, a few factors of potential importance were not explicitly considered in previous work. Firstly, in listening experiments with short fragments of noise, listeners assess the perceived annoyance of noise. Such assessments cover both perceived loudness and perceived character of noise (e.g., see [9]). However, for short fragments of sound, the temporal effect may partly contribute to the annoyance differences between trains and continuous traffic sound. Longer exposures, containing several train passages as well as the typical quiet periods in between, were

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necessary to include in this experiment. Secondly, in real life, sounds may be annoying also because they change adversely the current soundscape or are associated with a cultural change or they interfere with activities, for example, reading or relaxation. This latter "acute" but important aspect of noise annoyance is not captured in traditional listening experiments, but is possible to assess, if the experiment is designed in the right way, as shown in [10, 11]. Finally, it is well known from environmental noise questionnaire surveys that personal factors such as noise sensitivity influence annoyance reports [12, 13]. Some of these factors have also been observed in listening experiments [14, 15]. Therefore, the results may not be valid and it may not be possible to generalize beyond the subgroup, if this subgroup had not been selected carefully to match the population concerning these critical factors.

Recently, a small annoyance survey was conducted near the maglev line in Shanghai [16]. Such annoyance surveys are not possible in Europe, because the magnetic levitation system has not yet been implemented but for a test facility. Therefore a field experiment was specially designed to solve as many of the above mentioned issues as possible. The experiment differed significantly from the above cited earlier research. A realistic home-like setting was created, in which the panelists were asked to relax while exposed to longer fragments of sound, including quiet periods (Section 2.1). Traffic noise was reproduced in an ecologically valid way, using multiple loudspeakers outdoors to simulate pass-by sound (Section 2.2). The set of panelists was selected to be representative of the Dutch population in factors known to be important modifiers of noise annoyance (Sections 2.3). For the outline of the listening test, menus of train passages delimiting longer exposure durations were used (Section 2.4). The method of master scaling by which perceived annoyance was scaled, calibrated the scales used by different participants to a common master scale (Section 2.5).

2. The experiment

2.1. Sound reproduction in a realistic setting

As a natural setting, a holiday cottage in Westkapelle (Zeeland, The Netherlands) was selected because of its quiet environment and accessibility. During the experiment, subgroups of participants were seated in the living room, reading a magazine, engaging in light conversation or having something to drink. Figure 1 shows the cottage and its environment. Much attention was paid to creating a realistic reproduction of the three-dimensional indoor sound field, produced by a moving train outside the house. Observe that the goal was to obtain an "ecologically valid" [17, 18, 19] reproduction rather than physical precision, i.e. the methods, materials and setting are aimed at approximating the real-life at-home situation under study. It is difficult to produce the effect of any house by signal processing and playback through headphones or indoor loudspeakers, and to accomplish a natural feeling

Figure 1. Entrance through the garden to the holiday cottage (at the left) where the experiment was performed.

of the sound field. Therefore, it was decided to reproduce the sound field, as recorded outdoors, outside the experimental cottage.

A similar approach has recently been described in [11], where a laboratory test room was modified to mimick a standard living room. Traffic sounds were reproduced from behind a fake window by a 16-channel loudspeaker setup applying the wave field synthesis technique [20]. Our field experiment was conducted in a real living room, with the sound reproduction system installed outside the house in open air. Our setup therefore favors a more realistic and ecologically valid context in exchange for a less accurate sound field reproduction, as compared to [11]. The two-channel recording was, however, accurate enough for producing a realistic three-dimensional representation indoors. Neither approach can, however, completely relate to and account for the participants earlier experiences of noise annoyance in their own natural home environment.

In a small field study, the selected technique for realistic indoor representations of train passages was checked perceptually and acoustically for low speed trains at short distances. In another house situated close to a densely trafficed railway track, the indoor sound fields of real trains and of artificially reproduced train noise were compared. Two loudspeakers placed outdoors were used for reproducing the artificial passages of train noise. The procedure consisted of 2 phases. Firstly, during the passage of a train, the sound was recorded outdoor by 2 B&K 4189 free field microphones separated 20 m from each other along the track; for calibration, the façade level was also recorded. At the same time, a binaural recording was made inside the house. Secondly, the recorded sound was played back by 2 loudspeakers in front of the house, separated about 10 m from each other, and along the same horizontal axis as seen from the window. The volume was adjusted to reproduce the 1/3-octave band spectrum at the façade as accurately as possible. Simultaneously, a binaural recording was again made inside the house. Ideally both binaural recordings (real train and reproduced train) should be equal. For most trains the artificial sound could not be distinguished from

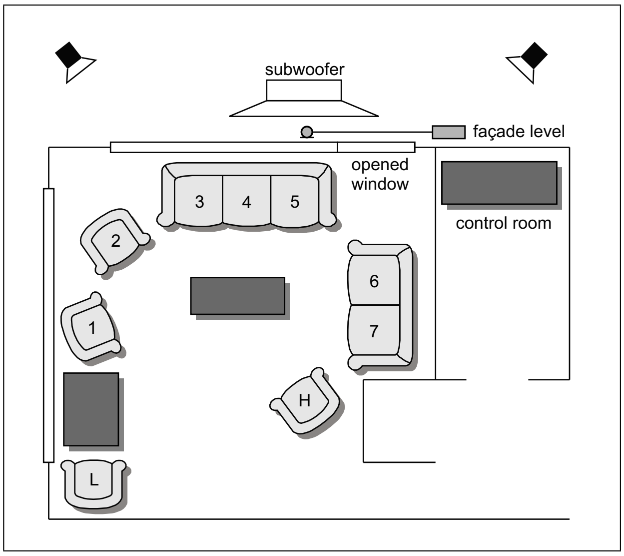

Figure 2. Schematic drawing of the experimental cottage (not to scale). The different seats of the panelists are shown (1–7), as well as the seat of the experimental leader (L) and of an artificial head (H) for binaural recordings.

the real sound by audition. The two spectra were in most 1/3-octave bands within an error of ca. 5 dB; nevertheless it was decided to introduce an equalizer for fine-tuning and a subwoofer for reproducing more accurately the low frequency part of a moving high speed train.

Figure 2 shows a floor plan of the living room and the control room of the experimental cottage, together with the final loudspeaker setup. The sounds were played back on a regular PC equipped with a high quality audio card, located in the control room. The sound signal was then equalized by an Allen & Heath 12-channel mixer and 31-channel equalizer. Subsequently, the sound signal was amplified by a Bose 802II amplifier and fed to 4 Bose loudspeakers, which were placed stacked per 2 on 2 tripod stands at a height of ca. 1.5 m, and to a HK Audio SL218A powered subwoofer on the ground. All loudspeakers were placed outside the house, in front of the main window. The 2 loudspeaker tripods were placed ca. 10 m from each other, perpendicular, at 3 m distance to the façade. The subwoofer was placed in front of the window in between both tripods, at about 50 cm from the façade. This loudspeaker setup was located in front of a slightly opened window of the experimental cottage, invisible to the panelists entering the house.

The façade level was measured continuously during all experimental sessions, using a B&K Investigator 2260 sound level meter with a B&K 4189 free field microphone (5 cm from the window at 75 cm height). The sound level meter was also used to calibrate the playback system. For this calibration, pink noise was played back and adjusted to give a façade level of 91 dB with a flat 1/3-octave band spectrum. The equalizer accomplished a flat (± 3 dB for all 1/3-octave bands) spectrum between 30 Hz and 16 kHz. The façade attenuation and the reverberation in the experimental room both modify the spectrum *and* temporal characteristics of the sound. Since it would not be possible to see a train passage from the window because of plenty of trees, a visual presentation of passing trains was considered not appropriate.

2.2. Sample collection and preparation

Two-channel recordings were conducted for three types of trains. Two microphones were placed at 20 m distance from each other along the track, 1.5 m above ground level. TGV trains at high speed were recorded in Beloeil (Belgium), a site near the TGV connection between Brussels and Lille (France). Dutch intercity (IC) trains of the new type (duplex) were recorded in Oudenbosch near Roosendaal (The Netherlands); at this same site the TGV traveling at low speed from Brussels to Rotterdam was also recorded. At the maglev test track in Lathen (Germany), the Transrapid 08 train was recorded at speeds of approx. 200 km/h, 300 km/h and 400 km/h. For the master scaling references, the sound of the E40 highway was also recorded near Ghent (Belgium). To be able to assess the influence on annoyance of the distance to the track, 4 recording distances were included (25 m, 50 m, 100 m, and 200 m). All recordings were made in free field without noise barriers. Not only the spectrum and temporal change were reproduced exactly, but also the sound level, as if the house would have been located at the measurement site.

From the many train recordings made at each site, the passages of highest quality were selected in each category of recording, and for these, 45-second single passage fragments were cut. It was important to expose the panelists to sufficient and natural durations of noise. Therefore, they had to be exposed to “experimental sound” during at least 10 minutes (henceforth called a menu). To create a realistic exposure situation within a 10-minute menu, it should be composed of the same train type, at the same distance and speed. Menus with 2 or 4 passages were created because 4 passages in 10 minutes already represents the natural time-schedule maximum, and 2 passages in 10 minutes represents a minimum passage rate with inter-passage background sound. Less than two passages are not useful because the inter-event silence is non-defined in this case. Apart from the 45-second fragments recorded at the four distances to the track, a 10-minute highway sound was recorded at 50 m distance to the closest lane.

Table I summarizes the sound exposure (ASEL) and sound levels ($L_{\mathrm{Aeq,45s}}$) associated with the 45-second passages used in the 10-minute menus. It should be mentioned that the level of the IC train at 25 m happens to be lower than the level at 50 m. This inconsistency is due to the fact that the selected high-quality sound fragments do not necessarily originate from identical train passages. There is always a natural spread in the speed and the number of wagons of the different passages of the same type of train. As an illustration, Figures 3 and 4 show the A-weighted sound exposure level in 1/3-octave bands for some of the experimental traffic sounds, as recorded in free field.

For master scaling, 7 traffic-noise-like reference sound fragments of 45 seconds duration, with sound pressure

Table I. Sound exposure levels (ASEL) for one 45-second train passage, sound level ($L_{\mathrm{Aeq,45s}}$) of one 45-second train passage and of highway traffic, and sound level ($L_{\mathrm{Aeq,10min}}$) of the 10-minute menus of the experiment, at 25 m to 200 m distance to track or route (all free field recordings). The train noise $L_{\mathrm{Aeq,10min}}$ values are given for the 2-train menu; to obtain the $L_{\mathrm{Aeq,10min}}$ values for the corresponding 4-train menu, add 3 dB.

Sound source		Outdoor ASEL [dB(A)]				Outdoor $L_{\mathrm{Aeq,45s}}$ [dB(A)]				Outdoor $L_{\mathrm{Aeq,10min}}$ [dB(A)]			
		25 m	50 m	100 m	200 m	25 m	50 m	100 m	200 m	25 m	50 m	100 m	200 m
Maglev	200 km/h	80.1	72.9	71.3	59.7	63.6	56.4	54.8	43.2	55.3	48.1	46.5	34.9
	300 km/h	86.3	83.0	80.3	69.6	69.8	66.5	63.8	53.1	61.5	58.2	55.5	44.8
	400 km/h	92.6	88.7	85.2	70.4	76.1	72.2	68.7	53.9	67.8	63.9	60.4	45.6
TGV	140 km/h	84.1	78.3	73.6	64.4	67.6	61.8	57.1	47.9	59.3	53.5	48.8	39.6
	300 km/h	92.8	90.6	86.9	83.0	76.3	74.1	70.4	66.5	68.0	65.8	62.1	58.2
IC	140 km/h	75.0	80.9	72.4	62.0	58.5	64.4	55.9	45.5	50.2	56.1	47.6	37.2
Highway	free flow	–	–	–	–	71.6	66.1	62.6	55.3	–	65.3	–	–

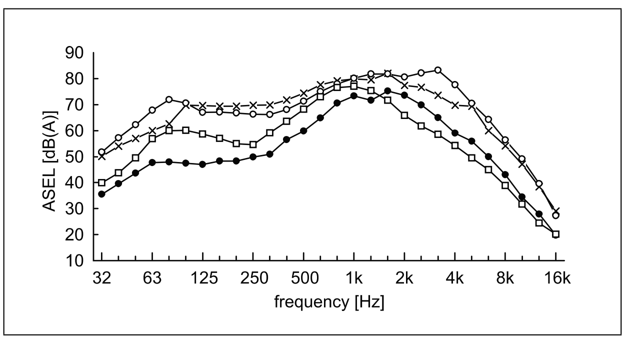

Figure 3. Sound exposure level (ASEL) in 1/3-octave bands of four different types of traffic sounds, all recorded during 45 seconds in free field at a distance of 50 m to the track (or highway route): (✕) a passage of a maglev train traveling at 400 km/h, (○) a passage of a TGV traveling at 300 km/h, (●) a passage of an IC train traveling at 140 km/h and (□) a highway with free flow traffic.

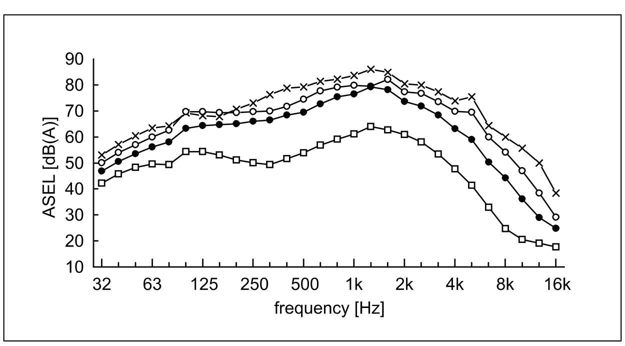

Figure 4. Sound exposure level (ASEL) in 1/3-octave bands of a maglev train traveling at 400 km/h, recorded during 45 seconds in free field at various distances to the track: (✕) 25 m, (○) 50 m, (●) 100 m and (□) 200 m.

level spanning the whole experimental range, were included in the experiment. A 45-second fragment of the highway noise recorded at 50 m distance to the highway was used as the centre reference sound. A filter which attenuates the sound at frequencies below 500 Hz by 3 dB and above 500 Hz by 6 dB was applied 3 times to produce 3 reference sounds with varying level, all below the level of the centre reference sound, giving the impression that the source is further away. In the same way, a filter that amplifies the sound at frequencies below 500 Hz by 3 dB and above 500 Hz by 6 dB was used to generate 3 reference sounds with varying level higher than the level of the centre reference sound.

2.3. Selection of a representative panel

In contrast to previous experimental work on noise annoyance caused by high speed trains, in which small "convenient" samples of test persons were recruited, the selection of panelists was here made to guarantee a representative sample of panelists. A questionnaire was administered at the doorstep of the homes of approximately 1500 persons, all living within a distance of 15 km from the experimental site. In an introductory letter, one inhabitant of the house was invited to participate in the study. The prerequisites were that (s)he had to fill in and send the questionnaire back to the address on the enclosed stamped envelope. A compensation of €100 was offered for participation.

The questionnaire contained selected questions that had been asked to a representative sample of the target population in a recent survey. The structure of the Dutch population was inferred to be representative from a recent RIVM survey [21] and partly from a Eurobarometer questionnaire. Our questionnaire contained (standard) questions on environmental noise as regards perception, annoyance and sleep disturbance. Included were evaluations of the quality of the neigbourhood in terms of housing and environmental pollution of other types than noise, as well as evaluations of overall satisfaction with the current living situation. Other questions addressed basic demographic variables such as age, gender, education, housing, family size and work arrangements. A set of questions were also included on general and mental health, hearing ability, environmental background, opinion and worry, and environmental sensitivity.

A procedure to draw panelists, representative of the target population, from the 255 replies received involved three stages. Stage 1 removed potential panelists on the basis of their age and hearing ability (information had already been given in the introductory letter). Stage 2 further removed those that were very dissimilar from the typical

Table II. Comparison between the panelists and the reference population on various criteria. Mean and standard deviation is shown; the results for the second series of criteria are on an 11-point scale and vary from 0 (not at all / bad) to 10 (very / good).

Criterium	Participants	Reference
Gender [% male / % female]	51 / 49	48 / 52
Age [year]	45.1 ± 13.4	45.6 ± 17.7
Noise sensitivity	5.1 ± 2.4	4.6 ± 2.6
Quality of traffic noise in the living environment	6.6 ± 2.4	6.4 ± 2.3
Quality of the living environment	7.6 ± 1.4	7.3 ± 1.3
Feeling afraid or frightened	2.4 ± 2.0	2.3 ± 2.1

Dutch person on the basis of binary coding of most of the other criteria included in the questionnaire. This stage implicitly assessed individual responses on the questions as regards their concordance with the response profile of the typical Dutch person in the reference survey. Stage 3 finally selected panelists on the basis of fuzzy resemblance to the typical Dutch person on the most critical criteria of annoyance surveys, such as age, gender, education, noise sensitivity, feeling afraid or frightened, hearing train noise at home, quality of traffic noise in the living environment, quality of the living environment, general health, and illness. Finally, ca. 100 representative participants were selected. Table II shows a comparison of the panelists with the Dutch target population as regards the mean and standard deviation of some of the selection criteria used and mentioned above.

2.4. Listening test outline

Four to six panelists jointly participated in a session. The overall structure and time schedule of the listening experiment was identical for each group of panelists. It started with a 14-minute training session, during which the panelists were asked to scale each of the 7 reference (highway) sounds two times (in random order). Thereafter, 7 10-minute menus were played, of which the first menu always was the highway traffic menu. A short break was then taken and the training session was repeated, after which again 7 new 10-minute menus were played. After this experiment with menus, a more conventional psychoacoustical listening test was conducted, in which the panelists had to scale 45-second excerpts of all transport noise stimuli used in the menu experiment. The duration of an experimental session was on average about 4 hours. To illustrate how the listening test was performed, Figure 5 shows the sound level in dB(A), rerecorded in front of the façade, during one of the panelist groups' listening experiment.

In all, two times 6 train menus were presented to each panelist. It was decided that, within one set of 6 train menus, conventional trains (IC or high-speed) should not be mixed with magnetic levitation trains. By this separation, it was possible to include a retrospective evaluation over the last hour as well. From previous experience it was known that the order of the menu pesentations might affect the results. Half of the panelists were therefore presented the maglev train sounds first, the other half the conventional trains first. A singular session consisted of the same number of passages inside the menus. This avoids that panelists would concentrate on counting events. Finally, since one distance to the track would create a natural setting, large distances were never mixed with short distances in the menus of a session.

During the experimental sessions, perceived noise annoyance of all transport noises was scaled with the method of free-number magnitude estimation [22]. The panelists were asked to write down their magnitude assessments on different coloured pieces of paper. Before the start of the experiment, the panelists were instructed to select an appropriate number and then to double this number if they found the next stimulus to be twice as annoying, to make the number three times larger if they found the next stimulus to be three times as annoying etc., and to scale 0 if they considered it not to be annoying at all. For each 45-second sound (training sessions and conventional listening test), a conditional question was included: “To what extent would you be annoyed by this traffic sound, if you heard it while relaxing?”. For each 10-minute menu a very similar, but retrospective question, was asked: “To what extent were you annoyed by traffic sound during the previous period?”. In these latter questions, we explicitly did not want to refer to train noise, since we wanted the panelists to decide themselves whether the sound period they last heard sounded like train-contaminated or not.

2.5. Master scaling

In all experimental sessions, the 7 road-traffic-noise-like reference sounds helped the panelists to define their own scaling context. The annoyance values given to these reference sounds made it possible to control for the individual panelists' choice-of-number behaviour in scaling the target train sounds. It would also control the influence of personal factors such as noise sensitivity. To get rid of these effects, each individual panelist's annoyance scale was calibrated by the aid of the reference to the common master scale [23].

A graphical illustration of the master scale transformation applied to the annoyance reference data of one of the panelists is given in Figure 6. The average annoyance reported for each of the 7 reference sound levels of road traffic noise is plotted in lin-log coordinates against their sound levels, $L_{\mathrm{Aeq,45s}}$, measured at the façade. Individual psychophysical functions are fitted to the reference data (open circles). They are of the form

$$A_r = a + b \log S_r, \qquad (1)$$

where A_r is the reported annoyance during the training session, and $\log S_r$ is the corresponding “road traffic noise” reference (r) sound level in dB(A). The constants a

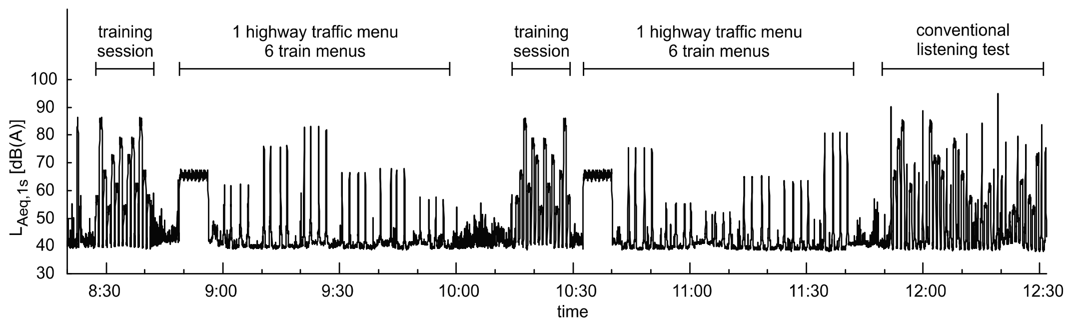

Figure 5. Sound pressure level rerecorded in front of the façade during one panelist groups' participation in the whole listening test: two training sessions, two menu sessions and one conventional psychoacoustical experiment with references.

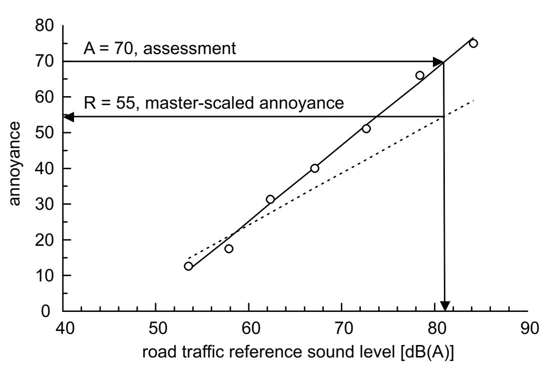

Figure 6. Calculation of master-scaled annoyance, using one panelist's empirical psychophysical function of the reference sounds (data points with solid line) and the master function for the same sounds (dashed line; obtained as average function for all panelists).

Table III. Test-retest reliability of panelists' perceived noise annoyance of the 7 reference road traffic sounds. Each cell contains an arithmetic mean of Pearson's coefficient (r) and its standard error. Ts1: Training session 1, Ts2: Training session 2, Ct: Conventional test.

	Ts1		Ts2		Ct
	Set 1	Set 2	Set 1	Set 2	Set 1
Ts2/2	0.82 ±0.015				
Ts2/1	0.86 ±0.014	0.87 ±0.016			
Ts2/2	0.86 ±0.017	0.88 ±0.020	0.87 ±0.019		
Ct/1	0.83 ±0.015	0.83 ±0.021	0.82 ±0.019	0.85 ±0.020	
Ct/2	0.84 ±0.015	0.85 ±0.019	0.81 ±0.016	0.84 ±0.019	0.82 ±0.015

and b will be different for each panelist and will depend on their choice-of-number behaviour in the particular scaling context. The empirically derived master functions for the group of 100 panelists (dashed line in Figure 6) were then used to transform the free number magnitude estimations of the train or road traffic menus for each individual, A_e, to the corresponding annoyance values R in master scale units,

$$R = -62.9 + 1.45\frac{A_e - a}{b}. \qquad (2)$$

The slope of the master function was set to 1.45, which is the average slope of all the individual psychophysical functions, whereas the intercept was set to produce a value of "zero" for the most quiet train menu. The reason for the latter choice was that a majority of the panelists (84 %) reported their annoyance to be zero for this menu, and a majority of the panelists reported annoyance to be greater than zero for all other menus.

The choice of a logarithmic psychophysical function (equation 1) was a compromise. In previous magnitude estimation experiments of loudness [23, 9], a power function of the form $\log A = c + d \log S$ was found to fit the empirical data best. However, in this experiment noise annoyance, rather than loudness, was scaled and thus, obviously, also a value of zero (= not at all annoyed) had to be handled, although the noise was heard and its loudness was above zero. The power function (after removal of zeros) did not fit the data better than the chosen logarithmic function.

2.6. Data quality analysis

The master scaling made it possible to investigate the quality of the experimental data in two ways, as panelists' test-retest reliability and as their scaling ability. The 7 reference sounds were presented 6 times to each panelist; twice in the two training sessions and twice in the last conventional listening test. The set of 6 reference scale values were used to determine each panelist's test-retest reliability of annoyance. Table III shows the Pearson's coefficient of correlation for these 6 annoyance scales, averaged over all panelists. The test-retest reliability was very good, between 0.81 and 0.88, and the standard error was low, between 0.014 and 0.019.

The deviation from the proposed master function (equation 1) was used to assess the data quality and annoyance

Table IV. Distribution of constants of the panelists' individual psychophysical functions (Eq. 1). The number of data sets refers to the average of 4 or 2 raw annoyance values, which was taken for each of the 7 reference sounds to calculate the psychophysical functions.

	Data Sets	Psychophysical function r^2	a	b
Training session 1&2	4	0.947	−67.27	1.449
		±0.077	±61.28	±1.230
Conventional test	2	0.881	−47.57	1.105
		±0.118	±48.17	±0.948

scaling ability for each panelist and to trace errors and inaccuracies. Table IV shows the distribution of constants of the panelists' individual psychophysical functions (equation 1). The average annoyance variance explained by sound level ($L_{\mathrm{Aeq,45s}}$) of the reference road traffic sounds was found to range from 88 % to 95 %. All panelists were able to produce acceptable individual logarithmic functions of annoyance as a function of sound level to the reference. They have thus produced acceptable annoyance data in order to transform these to a common master scale of annoyance; no panelists were excluded from further data analysis.

3. Results

The main listening experiment with menus differed from previous laboratory experiments in a number of aspects. One important novelty is that participants were asked to judge annoyance over a longer period of time — Fastl and Gottschling's experiment [4] forms an exception. During the 10-minute periods, the panelists were engaged in low attention, relaxing activities such as reading a magazine, making a conversation or having something to drink. In order to find out how this new approach affected the results, a subsequent experiment was included, which was more comparable to earlier experiments on train noise (e.g. [8]).

3.1. Main field experiment with 10-minute menus

The panelists' master scale values of annoyance were averaged for each menu in the field experiment. A stepwise multiple linear regression analysis was performed, with average master scaled annoyance as dependent variable and (a) time averaged A-weighted façade exposure $L_{\mathrm{Aeq,10min}}$, (b) distance to the source (logarithmic) and (c) source type, as independent variables. Because of its legislative importance in the Netherlands, the façade exposure was preferred to the actual panelists' noise exposure. Façade exposure was calculated from the sound levels measured on the recording sites, since the façade levels measured during the experiment also contain noise from wind and rain. It has to be noted that the actual sound exposure levels experienced by panelists participating in a single experimental session may differ, because of different seating positions. However, personal characteristics, such as noise sensitivity, will have a much larger influence

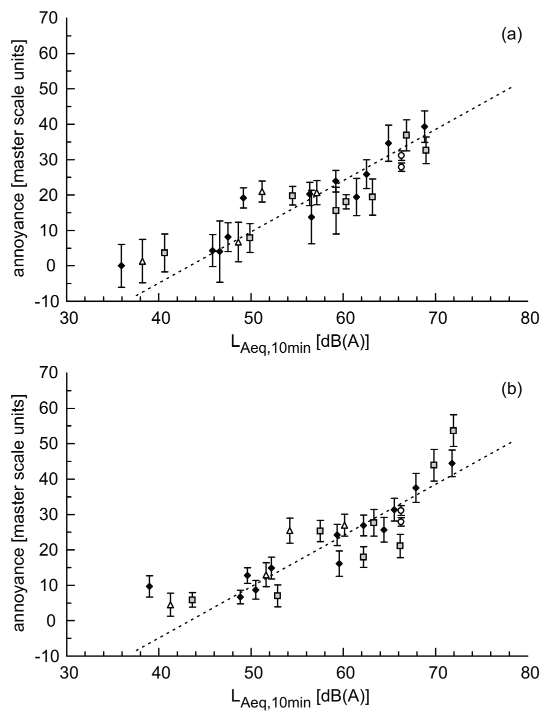

Figure 7. Average master scaled annoyance of the menus versus $L_{\mathrm{Aeq,10min}}$ (a) for 2 events per 10-minute menu and (b) for 4 events per 10-minute menu, for different types of train sounds: (△) IC train, (□) TGV and (◆) maglev train. In comparison, the annoyance for the highway traffic (○) is also shown. Standard error on means is indicated, as well as the master function (dashed line).

on perceived annoyance, as compared to the influence of a slightly different exposure.

Table V summarizes the results. In the first model, sound level was the only independent variable; this model explained 80 % of the variance in annoyance. In the second model, distance to track was added to sound level as an independent variable; this model increased the variance explained to 85 % (F-change = 14.49; $df_1 = 1$; $df_2 = 46$; $p < 0.001$). Thus, distance to source explained a significant additional part of the annoyance variance not accounted for by sound level. In the third model, source type was included as a third independent variable along with sound level and distance. Source type was defined on a nominal scale: MAGLEV, TGV, IC and HIGHWAY. It was introduced in the analysis as three dummy variables, coded 0 and 1 (the highway noise source type corresponds to the case that these variables are all zero). The inclusion of source type did not increase significantly (F-change < 1.0) the proportion of variance explained. This suggests that statistically, there is no additional contribution of source type on perceived annoyance over and above the effects of sound level and distance. It can therefore be concluded that magnetic-levitation based transportation systems are not significantly more annoying than conventional rail based systems (same façade L_{Aeq} and same distance are prerequisites). Moreover, railway noise was not found to be

Table V. Stepwise multiple regression analysis of acoustic variables on perceived annoyance of train and highway traffic sounds, for the main field experiment with 10-minute menus. The Pearson's correlation coefficients of the variables entered in the regression analysis are shown at the bottom. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Model	Model fit (r^2)	Model fit increase (r^2-change)	F-change	Independent Variables	Coefficient	t-value
1.	0.80	0.80	187.48^{***}	$L_{\mathrm{Aeq,10min}}$ [dB(A)]	1.18	13.69^{***}
2.	0.85	0.05	14.49^{***}	$L_{\mathrm{Aeq,10min}}$ [dB(A)]	0.92	9.17^{***}
				$\log_{10}$(distance [m])	−10.74	-3.81^{***}
3.	0.85	0.00	0.13	$L_{\mathrm{Aeq,10min}}$ [dB(A)]	0.96	8.22^{***}
				$\log_{10}$(distance [m])	−10.17	-3.33^{**}
				MAGLEV [0,1]	1.45	0.27
				TGV [0,1]	0.85	0.16
				IC [0,1]	2.27	0.40

Label	Variable	ANN	LEQ	DIST	MAG	TGV
ANN	Annoyance [master scale]					
LEQ	$L_{\mathrm{Aeq,10min}}$ [dB(A)]	0.894				
DIST	$\log_{10}$(distance [m])	−0.754	−0.659			
MAG	MAGLEV [0,1]	−0.023	−0.038	0.009		
TGV	TGV [0,1]	0.132	0.224	0.006	−0.682	
IC	IC [0,1]	−0.179	−0.290	0.004	−0.433	−0.308

systematically less annoying than highway traffic noise. This means that no support for a railway bonus was found in this experiment; at least it was not as obvious that it could be observed using linear statistics. Figure 7 gives an overview of the annoyance functions for the 10-minute menus as a function of $L_{\mathrm{Aeq,10min}}$. The dashed line indicates the master function of annoyance for the road-traffic-like sounds used as references.

The shorter rise time of the noise of arriving high speed trains may create more annoyance than a conventional train can do. Figure 8, Panel a, shows the rise speeds in dB(A)/s in proportion to circle sizes. These values were calculated for all sound events included in this experiment by fitting a straight line through the initial increase in sound level. The accelerating growth of annoyance with increasing L_{Aeq} may be explained by the rise time. In Figure 8, Panel b, the size of the circles is instead proportional to the distance to the track. For L_{Aeq} in the interval between 50 and 65 dB(A), annoyance is clearly lower for train passages at larger distances than for train passages at closer distances or road traffic noise (dashed line). This could indicate that a possible noise annoyance bonus for train noise would only hold at larger distances from the track, and only in the latter L_{Aeq} interval.

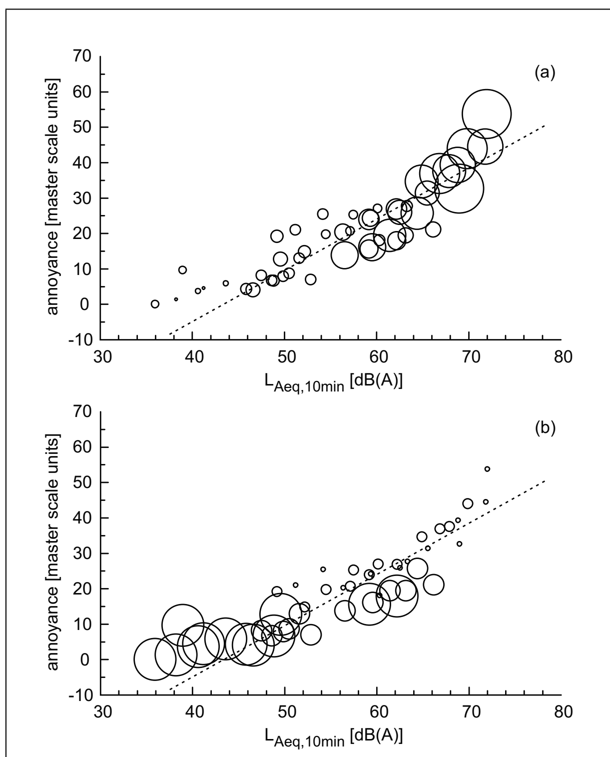

Figure 8. Average master scaled annoyance of the menus versus $L_{\mathrm{Aeq,10min}}$ showing (a) the noise event rise speed and (b) the distance to the track as the size of the circles. The master function is also indicated (dashed line).

3.2. Conventional listening test

In the conventional listening experiment, the sounds were presented as short 45-second fragments containing the sound of one train passage and highway excerpts. Figure 9 shows the results of these master scaled annoyance values as a function of time averaged A-weighted façade exposure, $L_{\mathrm{Aeq,45s}}$. A railway penalty can be observed, both in regard to the artificial reference sounds as well as to the highway sounds. Figure 10 shows the annoyance as a function of rise speed (Panel a) and distance to the track (Panel b).

Table VI. Stepwise multiple regression analysis of acoustic variables on perceived annoyance of train sounds (no highway traffic sounds), for the conventional listening test (45-second passages). The Pearson's correlation coefficients of the variables entered in the regression analysis are shown at the bottom. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Model	Model fit (r^2)	Model fit increase (r^2-change)	F-change	Independent Variables	Coefficient	t-value
1.	0.95	0.95	420.17***	$L_{\mathrm{Aeq,45s}}$ [dB(A)]	1.67	20.50***
2.	0.98	0.03	12.50***	$L_{\mathrm{Aeq,45s}}$ [dB(A)]	1.23	11.04***
				Speed [km/h]	0.02	2.03
				$\log_{10}$(distance [m])	−1.78	−0.77
				Rise speed [dB(A)/s]	0.63	3.65**
3.	0.99	0.01	0.98	$L_{\mathrm{Aeq,45s}}$ [dB(A)]	1.08	6.85***
				Speed [km/h]	0.03	2.09
				$\log_{10}$(distance [m])	−4.76	−1.46
				Rise speed [dB(A)/s]	0.58	3.30**
				MAGLEV [0,1]	−0.70	−0.37
				TGV [0,1]	1.66	1.04

Label	Variable	ANN	LEQ	SPD	DIST	RISE	MAG
ANN	Annoyance [master scale]						
LEQ	$L_{\mathrm{Aeq,45s}}$ [dB(A)]	0.975					
SPD	Speed [km/h]	0.646	0.541				
DIST	$\log_{10}$(distance [m])	−0.613	−0.667	−0.001			
RISE	Rise speed [dB(A)/s]	0.885	0.804	0.708	−0.437		
MAG	MAGLEV [0,1]	0.070	−0.017	0.552	0.000	0.188	
TGV	TGV [0,1]	0.207	0.246	−0.190	0.000	0.100	−0.707

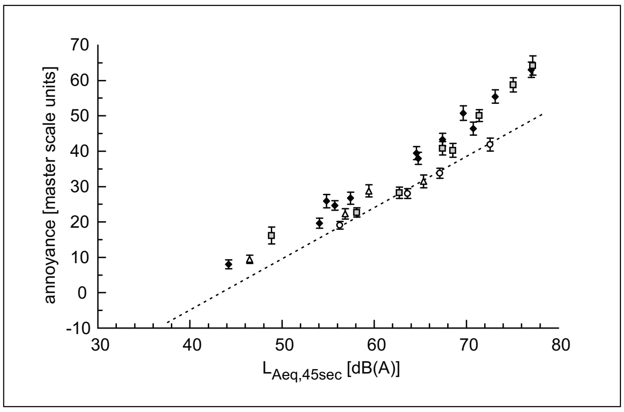

Figure 9. Average master scaled annoyance versus $L_{\mathrm{Aeq,45s}}$ for the conventional listening test, for different types of train sounds: (△) IC train, (□) TGV and (◆) maglev train. In comparison, the annoyance for the highway traffic (○) is also shown. Standard error on means is indicated, as well as the master function (dashed line).

A stepwise multiple linear regression analysis was also performed separately for the train noises (Table VI). The first model, in which sound level $L_{\mathrm{Aeq,45s}}$ was included as the only independent variable, explained 95 % of the variance in annoyance. In the second model, train speed, distance to the track and rise speed were added to sound level as independent variables. This increased the variance explained to 98 % (F-change = 12.50, $\mathrm{df}_1 = 3$; $\mathrm{df}_2 = 19$; $p < 0.001$). Apart from sound level, also rise speed contributed significantly to the variance explained. The third model, in which train type was added as an independent dummy variable, did not significantly increase the proportion explained variance (F-change < 1.0). These results suggest that, in this conventional listening test, there is no difference in perceived annoyance between different types of trains, over and above the effect of sound level and rise speed.

One has to note that the number of responses to each stimulus was smaller in the main experiment (10-minute menus) than in the conventional listenig test (45-second passages). This explains why the standard errors are lower and the explained variance is higher in the latter experiment.

4. Discussion

The annoyance results of the present field experiment are close to residents' everyday reality, although comparison with published studies is somewhat limited. Previous laboratory experiments on noise annoyance of conventional IC and high-speed trains, specifically magnetic levitation trains [8, 5], report significant differences for these types of sound. In particular, the results have shown that for the same L_{Aeq}, high-speed trains were more annoying than other trains. Compared to road traffic noise, the cited studies claimed a lower annoyance level for conventional trains. In the present field experiment, we did not find support for any annoyance difference between various types

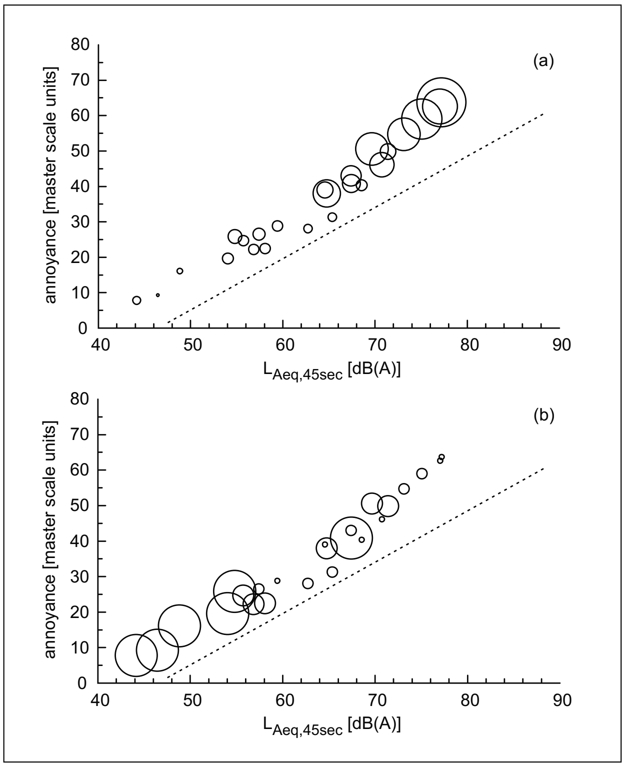

Figure 10. Average master scaled annoyance versus $L_{\mathrm{Aeq,45s}}$ showing (a) the noise event rise speed and (b) the distance to the track as the size of the circles. The master function is also indicated (dashed line).

of trains and road traffic. Some possible explanations will be given in the following subsections.

4.1. Realistic listening situation with 10-minute menus

The experiment was performed in a realistic setting, in which outdoor transportation noise was reproduced, and natural outdoor-to-indoor sound propagation characteristics were utilized (slightly open window). This setting provided a realistic sound environment indoors. Subgroups of panelists were kept indoors during the four-hour experiments, and upon request, annoyance to transport noise was reported with reference to 10-minute periods.

Because trains run on expected schedules to which people habituate, the experimental situation in classical experiments is rather unrealistic. The experimental one-passage situation [8] requires full attention and will have a large variation of train sounds, compared with a particular railway track. The outcome will to a large extent depend on the experimental context, that is, the variation introduced in the experiment by selecting stimuli and using random presentation orders. Random orders of recordings can be selected and arranged so that annoyance judgments on category scales plotted against sound level differentiate well or not well on type of transport. In the present field experiment, sub-context in sessions was kept invariant, similar to the situation on a real railway track. The judgmental context will then be much more restricted, as is the case when living along one railway track.

Next to this, the annoyance reports of the one 45-second train passage were higher than those of two passages of the same train within the 10-minute menus. This is all in order, because the two types of annoyance were master scaled in order to become comparable over experimental sessions. When judging 45-second train passages immediately after exposure, it is quiet clear that the task is to assess the annoyance of that particular train passage (or other sounds that were presented). However, when asked to assess the annoyance, retrospectively, of the transport noise during the last 10-minute menu (e.g. two train passages), the panelist will have to choose a strategy on how to go about this. For example, the annoyance may only be referred to the two noise-stimulus periods, or to the whole 10-minute period (menu). It has been shown that the noise annoyance of two overlapping (equal) noises would be expected always to be less than the arithmetic sum of the two annoyances (for a review, see [24]). It is more uncertain how total annoyance of two train passages separated in time will actually be acquired. A laboratory experiment, which included long sound fragments [4], has not found the above-mentioned annoyance difference between different train types, which is in line with our results.

4.2. Advanced scaling methodology

Long-term retrospective annoyance asked for in questionnaire surveys has typically been assessed on category scales (e.g. [3]). A response category is then implicitly postulated to be identical for every participant, by verbal labeling of the two end points or of every response box; also the intervals between categories are assumed to be the same. However, this assumption does not hold true [25]; e.g. in questionnaire surveys, the response criteria (scale value or category borders) for annoyance are much higher for respondents in low noise areas as compared to those in highly exposed areas. The most well known scaling bias in laboratory experiments is the context effect in which participants distribute their responses over the "full" range of categories, independent of the size of the exposure range (for a review, see [22]). In the process of using category scales, floor and ceiling effects on annoyance may also appear.

To avoid uncontrolled context effects an invariant sound level range of references was used as the annoyance context in the present field experiment. Continuous road traffic noise was chosen as a reference instead of multiple event sounds, because it is simpler to reproduce in future studies. To avoid the scaling bias of category scales the method of magnitude estimation was chosen, in which participants were free to use the range of numbers they felt comfortable with. Master scaling was applied to these individual annoyance estimates, involving a transformation function to a common master scale defined by the references, which sound levels defined the scaling context. In theory, this master scale transformation will calibrate the loudness-dependence of noise annoyance, whereas the relative contribution to noise annoyance from qualitative content (e.g. the type of sound, the time pattern and cues for speed and distance) will hopefully be unchanged.

Earlier research has shown that master scaling with references works well for loudness or annoyance of a one-occasion target exposure, that is, when repeated exposure is unfeasible (e.g. experiments with long duration exposures) or impossible (e.g. questionnaire surveys in field studies); an example can be found in [23]. The results obtained from the present field experiment are probably more reliable than the results that would have been obtained by category scaling. The test-retest reliability of the panelists' magnitude estimates of annoyance of the reference sounds was found to be very good (above 0.8) compared to the reliability of 0.72 obtained in [8] for a group of 12 much younger subjects. Considering that our panelists all were naïve participants, they also each produced high quality psychophysical functions for the reference, as discussed in Section 2.6.

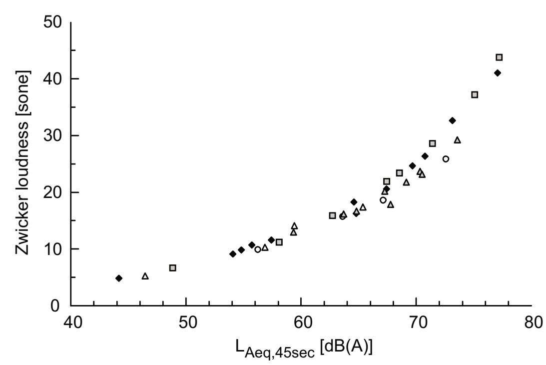

Figure 11. Zwicker loudness versus $L_{Aeq,45s}$ for different types of transportation sounds: (△) IC train, (□) TGV, (◆) maglev train, (○) highway traffic and (△) some additional noisier IC trains (older type).

4.3. Other possible explanations

There are several reasons why other investigators have found a railway bonus (for a review, see [3]), which was not found in this field experiment. One of the reasons for finding a railway bonus for short (one minute) noises in listening experiments, may be that the relation between loudness and L_{Aeq} is inherently different for train and road traffic noise. Indeed, some researchers have argued that noise annoyance evaluation in listening tests of short sounds actually is close to a perceptual loudness evaluation (however, see [26] on differences between loudness-based and quality-based perceived annoyance). If Zwicker loudness is a good first estimate of perceptual loudness, the difference between train noise (of different types) and highway noise would be seen in a Zwicker loudness versus L_{Aeq} plot (Figure 11). Because the IC train noise used in the present experiment was the noise of modern, rather quiet trains, a few older and noisier IC train models were added in this acoustic analysis. At levels above 65 dB(A), TGV and maglev trains seem to be a little louder than highway traffic or older IC trains. However, this effect on Zwicker loudness is not significant and does therefore not support a railway bonus of 5 dB(A), stipulated in several countries' legislation. Rather, it seems to be a good action to start to replace old IC trains by new ones. The railway bonus was originally based on studies with rather old low-speed trains, and with much less dense traffic intensity than nowadays.

The intermittent character of railway noise could also be an explanation for the railway bonus. However, this does not hold for aircraft noise, which is also intermittent; this can be explained by a difference in exposure. In the case of aircraft noise, the exposure is on top of buildings and on all façades. In the case of road traffic noise, the probability is high that there are local roads also, but there is a possibility for a "quiet side"; people are less annoyed if quiet sides are available [27]. In the case of railway noise, there is a low probability for the presence of more than one track, so the exposure will also be directed at only one façade. In comparing road traffic and trains, the façade insulation will be more effective in the case of train noise, because of the smaller low-frequency proportion associated to train noise. In comparing aircraft and trains, which are both intermittent, the indoor exposure is certainly more intensive for aircraft. Considering these arguments, it seems obvious that aircraft is more annoying than road traffic, which is more annoying than train. However, façade reduction was taken into account in the present field experiment, and still there was no clear railway bonus found. Compared with the field condition with closed windows, and the façade filter used in [8], a partially open window was used in the present field experiment, which could explain this.

In surveys questioning people at their home, a lower reported annoyance for train noise compared to highway traffic noise was observed in a particular range of noise levels. Most of the possible explanations proposed in literature conflict with the fact that this railway bonus would be observed in experiments based on single passages. We mention just a few. The typical character of train noise and the concentration of the sound energy in short time intervals may be advantageous with regard to activity disturbance. If the level is sufficiently low, the probability of noticing the train noise is small compared to the probability of noticing the sound of a continuous source. In addition to physical differences in the sound, the "green image" of trains as a means of transportation may add to the acceptability of the source and thus increase the tolerance to its noise, that is as long as train passages are not too frequent. However, a more recent hedonic pricing study found that householders in Birmingham place a greater value on reductions in railway noise than in road traffic noise [28]. Cross-cultural studies (in field and laboratory context) have shown that a railway bonus is not universal [29, 30], which would favor the argument above. It has further been shown that the bonus varies depending on the (multiple) exposure situation [31]. Based on the above, only part of the effect is supposed to be visible in field experiments such as the one reported of in this paper. Part of the effect is precisely what is observed.

5. Conclusion

This study has shown that in an "at home" like context, noise annoyance caused by different types of trains at the same average outdoor façade exposure level is not significantly different. In particular, magnetic levitation systems are not more annoying than conventional high speed trains, which is in agreement with earlier research. Noise annoyance caused by conventional trains was not found to be significantly lower than annoyance caused by TGV's or maglev trains at the same average façade exposure. Field surveys have shown that for the same average sound level, railway noise causes less annoyance or highly annoyed persons than highway traffic noise. Although our field experiment included several factors that may contribute to this effect, we could not observe it.

More insight may be gained by taking into account the psychoacoustic characteristics of the noise exposure and the relevant personal factors of the panelists. This paper has focused on discussing the experimental methodology in great detail, and on presenting the results as a function of the average outdoor façade exposure level, since this is the main noise legislation indicator used in the Netherlands. Results of a detailed psychoacoustic analysis will be reported in a future paper.

Acknowledgments

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