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Effects of road traffic noise and the benefit of access to quietness

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Abstract

Socio–acoustic surveys were carried out as part of the Soundscape Support to Health research programme to assess the health effects of various soundscapes in residential areas. The study was designed to test whether having access to a quiet side of one's dwelling enhances opportunities for relaxation and reduces noise annoyance and other adverse health effects related to noise. The dwellings chosen were exposed to sound levels from road traffic ranging from about $L_{\mathrm{Aeq,24h}} = 45-68\,\mathrm{dB}$ at the most-exposed side. The study involved 956 individuals aged 18–75 years. The results demonstrate that access to quiet indoor and outdoor sections of one's dwelling supports health; it produces a lower degree and extent of annoyance and disturbed daytime relaxation, improves sleep and contributes to physiological and psychological well-being. Having access to a quiet side of one's dwelling reduces disturbances by an average of 30–50% for the various critical effects, and corresponds to a reduction in sound levels of ($L_{\mathrm{Aeq,24h}}$) 5 dB at the most-exposed side. To protect most people (80%) from annoyance and other adverse effects, sound levels from road traffic should not exceed ($L_{\mathrm{Aeq,24h}}$) 60 dB at the most-exposed side, even if there is access to a quiet side of one's dwelling ($L_{\mathrm{Aeq,24h}} \leqslant 45\,\mathrm{dB}$).

1. Introduction

Environmental noise is recognized as a major health problem. The adverse health effects (i.e. general annoyance, speech interference, and sleep disturbances) of transportation noise are well documented [1]. Unlike many other environmental problems, noise pollution is still worsening. Thus, since 1992 it is the only environmental impact in Europe about which public complaints have increased [2]. In Sweden, the number of persons exposed to traffic noise exceeding outdoor guidelines ($L_{\mathrm{Aeq,24h}} = 55\,\mathrm{dB}$ and $L_{\mathrm{Amax}} = 70\,\mathrm{dB}$) is approximately 2 million or 25% of the population. In 1998, 840 000 people were estimated to have been exposed in their dwellings to road, air, and railway traffic noise exceeding indoor guidelines ($L_{\mathrm{Aeq,24h}} = 30\,\mathrm{dB}$ and $L_{\mathrm{Amax,\,22-06}} = 45\,\mathrm{dB}$) [3]. Nearly one million adults, or 22% of the Swedish population, are disturbed by noise in their homes; traffic and neighbours are the noise sources that annoy most people [4]. In residential areas, road traffic is normally the dominant noise source, and estimates show that road traffic will grow by 29% from 1997 to 2010 for personal transport [5] and by 25% for freight transport [6]. This increase is unsustainable and strategic action is required to reduce the adverse effects of such environmental noise. The Swedish government [7] has formulated long-term goals for the sustainable development of the

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built environment. One goal for 2020 is that no one should be exposed to sound levels above the indoor and outdoor guidelines. A wide gap prevails, however, between the existing noise environment and the long-term goals formulated by authorities in European countries. Development of methods to reduce noise at source (new road surfaces, etc.) will be inadequate to reverse the present negative trend. Recent studies show that over the past 25 years, noise emissions from individual road vehicles in normal traffic have decreased only by 1–2 dB (e.g. Ref. [8]). A new approach is needed if an acceptable noise environment is to be achieved in a reasonable time frame. Such an approach must be supported by scientific evidence.

2. Background and research strategies

The Swedish multi-disciplinary research programme Soundscape Support to Health has formulated a strategy for improving sound environments in residential areas. This strategy supports personal health and well-being and could potentially reverse the trend toward increasing adverse health effects of noise in residential areas. The programme aims to combine methods to abate emissions from noise sources (primarily road traffic) with optimal soundscape design. The intention is to create supportive, sustainable sound environments rather than merely to avoid unwanted noise. The goal is that every resident should be able to live a healthy and rich life free from: (a) direct as well as cumulative adverse health effects from noise (e.g. annoyance, stress-related psycho–physiological effects, and disturbed relaxation and sleep), (b) adverse effects on future generations (e.g. impaired residential, social, and learning environments), and (c) negative cultural, aesthetic, and economic effects (e.g. social isolation, run-down neighbourhoods, and lower property values).

Soundscapes in residential areas vary with space and time. Great variation can result from acoustical shielding by buildings and sound barriers. For optimal application in city and traffic planning, thorough knowledge of such soundscape variations and how these are perceived and used by the residents is crucial. The research in the programme focuses on developing methods to measure, design, and use noise barriers, through the design and orientation of buildings and landscapes, to create noise-shielded quiet areas. This approach involves using health-based soundscapes that, combined with newly developed methods to reduce noise emissions, should significantly improve the traffic noise problem.

The main goal of Soundscape Support to Health, Phase I (2000–2003), is to develop scientific bases, methods, and models for predicting and optimizing acoustic soundscapes in traffic noise-exposed residential areas, with respect to effects on perceived soundscapes and on health and well-being (including sleep). The programme also emphasizes strategic considerations for effective noise policy in the future. Such policy should promote supportive sound environments by: (a) setting health-based targets for sound environments, (b) establishing new guidelines for land-use and transport-system planning with regard to strategic environmental health evaluations of various abatement procedures, and (c) providing information and education on the effects of noise and the efficiency of various noise abatement procedures.

3. Aim of the studies on adverse health effects

The scientific aim of the health and well-being studies in the research programme was to explore how various adverse health effects, behaviours, and self-estimated noise sensitivity relate to individual acoustic and perceived soundscapes (including when subjects have access to a quiet side in their dwellings). Within the programme three projects have been conducted to assess health effects of soundscapes: (i) cross-sectional, (ii) longitudinal, and (iii) experimental/quasi-experimental studies on sleep [9].

The cross-sectional studies reported in this paper had three main aims. The first aim was to evaluate how having access to quiet indoor and outdoor sections in one's dwelling affected residents' annoyance, activity interference, sleep disturbance, and overall well-being. The second was to define criteria for characterizing residential acoustic soundscapes supportive of health and well-being. The final aim was to assess the association between self-estimated noise sensitivity and general annoyance.

4. Method and materials

4.1. Overall design of empirical studies on adverse health effects

Adverse health effects were empirically examined in cross-sectional field studies conducted in carefully selected residential areas during a 3-year period (2000–2002). Health and well-being effects were assessed using questionnaires (accompanied with an introductory letter) sent to the selected population samples. Sound levels from road traffic were then assessed by calculations and measurements. Data from 956 individuals regarding various health effects were linked to data regarding individual acoustic soundscapes and stored in an SPSS datafile for analysis. A subsample of this dataset was also linked to individual-level data regarding perceived soundscapes obtained from studies of 106 individuals (not reported in this paper).

Fig. 1 shows the overall design and research strategies of the research programme. A new calculation method for road traffic noise exposure assessment at the quiet side of a dwelling was developed. The soundscapes could then be linked to health and well-being effects for dwellings with and without access to a quiet side. "Soundscapes" are defined as the sound variations in space and time caused by the built-up topography of the city and its various sound sources. "Acoustic soundscapes" are soundscapes as described using acoustical variables; these soundscapes are assessed using physical measuring instruments. "Perceived soundscapes" are soundscapes described with the aid of perceptual variables; these soundscapes are assessed using perceptual scaling methods employing persons.

4.2. Study sites—description and selection criteria

Considerable effort was put into designing the empirical field studies and in selecting the various study sites. Five study sites were selected in which sound levels ($L_{Aeq,24h}$) ranged from 45 to 65 dB, free field value, at the most-exposed side of the dwellings. Half the dwellings in each of the five sites should have the same sound levels at both sides. The other half of the dwellings should have these sound levels at their most-exposed side, but approximately 10–20 dB lower sound levels at the quieter side (i.e. $L_{Aeq,24h} = 35$–45 dB).

The *preliminary* selection of study sites was based on the following set of criteria; (1) The roadside noise exposure should be similar in each pair of exposure categories. (2) The two pairs of study sites should preferably be in the same residential area, e.g. situated along the same road. (3) All dwellings in each noise category should have the same exposure to road traffic noise, within a ± 2 dB range. (4) The sites should be exposed to varying road traffic, e.g. not only light traffic or only heavy vehicles. (5) No other dominant noise

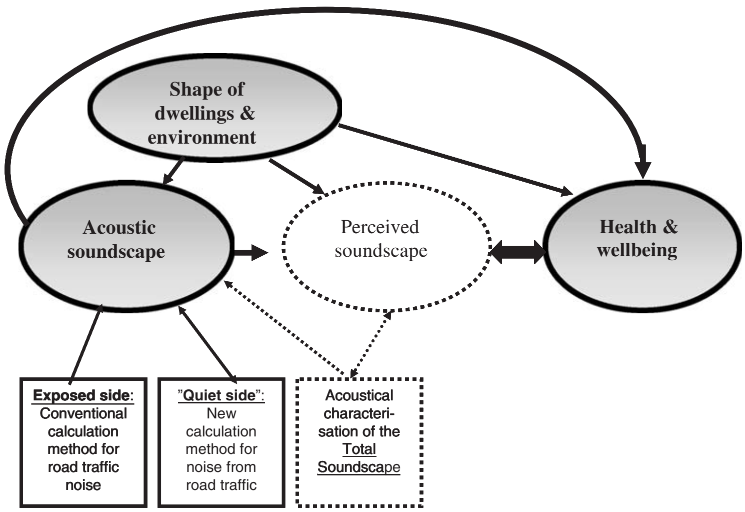

Fig. 1. Overall design and research strategies.

source should be present, e.g. rail or aircraft noise or noise from ventilation in the courtyards. The preliminary selection of study sites based on these criteria was executed by a consultant, Ingemansson Technology AB.

A second set of criteria covered the physical characteristics of the study sites, as follows. (6) Houses should be similar in terms of height and type (block of flats only). (7) Each dwelling should have at least two rooms in addition to a kitchen. (8) The dwellings should preferably have rooms facing two sides (i.e. both the road and the courtyard side) of the building. (9) Each dwelling should preferably have access to a balcony or an outdoor space. (10) The type of window should preferably be known.

A third set of criteria covered the population characteristics of study sites, as follows. (11) The ages of subjects and proportion of people born abroad should not vary greatly from site to site. (12) If possible, only people who have resided in the dwelling for at least 1 year should be selected to participate. (13) At least 125 dwellings in each pair of sites should be available for selection according to the above criteria.

Each study site was documented by aerial photographs, photos of the outdoor environment, and photos of the building façades. All short- and long-term noise measurement points were marked on these photos. In selecting dwellings and calculating individual noise dose immission levels, the following information sources were utilized: (1) documentation of study sites and buildings as well as maps (scale, 1:4000) with elevation contours; (2) blueprints of dwellings; and (3) data from the questionnaire concerning floor level and side of the building faced by the balcony, bedroom windows, and living room windows.

4.3. Evaluation of adverse health effects of noise

The study focuses on perceived adverse health effects (e.g. annoyance, sleep quality, and well-being) of road traffic noise, but does not examine its physiological effects (e.g. hypertension and cortisol levels). The frame of reference of this project is that situational aspects (e.g. access to a quiet side of a dwelling, orientation of rooms, and presence of balconies and outdoor space for relaxation) act as modifiers between noise immission and various annoyances that have long-term effects on health and well-being. To evaluate the adverse health effects, a questionnaire was constructed based on previous questionnaires used in cross-sectional studies [10–12]. The questionnaire was adapted to the specific situations of the various residential sites chosen for the study. The questionnaires were distributed by mail, and an accompanying introductory letter presented the research as a study of well-being and the general living environment. One or two reminder letters were sent to recipients who did not answer within 10 days.

The questionnaire contained batteries of questions concerning: (1) subjects' living environment and residences and various sources of nuisance; (2) noise annoyance and interference with various activities both indoors (open and shut window) and outdoors; (3) work situation, socio–demographic factors, and self-estimated noise sensitivity; (4) perceived sleep quality; and (5) general physical health and mental well-being. The questionnaire also evaluated the use of various indoor and outdoor spaces and their locations (e.g. sleeping quarters, living room, kitchen, balcony, and common outdoor areas for relaxation).

In the questionnaire, annoyance stemming from road traffic noise was evaluated using three scales. A 5-point category scale [10,13] was used in a battery of questions concerning various sources of annoyance (“don't notice” = 0, “notice but not annoyed” = 1, “slightly annoyed” = 2, “moderately annoyed” = 3, and “very annoyed” = 4). Two ISO standardized annoyance scales were used [14]. A verbal 5-point category scale (“not at all annoyed” = 1, “slightly annoyed” = 2, “moderately annoyed” = 3, “very annoyed” = 4, and “extremely annoyed” = 5) and a numeric 0–10 scale (endpoint markings “not at all annoyed” and “extremely annoyed”). The verbal standardized annoyance question was phrased, “Thinking about the last (12 months or so), when you are at home, how much does noise from road traffic bother, disturb, or annoy you?” The numerical annoyance question was phrased “Thinking about the last (12 months or so), what number from 0 to 10 best shows how much you are bothered, disturbed, or annoyed by road traffic noise?”.

Disturbance of different daytime activities by road traffic noise (communication, listening to radio/TV, relaxation, concentration, and opening windows) and disturbances of sleep (opening bedroom windows, falling asleep, awakenings, and sleep quality) were evaluated by two questions regarding (i) how often (“never” = 0, “sometimes” = 1, and “often” = 2) and (ii) to what degree (“slightly disturbing” = 2, “moderately disturbing” = 3, and “very disturbing” = 4) respondents were disturbed by road traffic noise. The questions concerning “how often” were phrased, “How often does noise from road traffic disturb, for example, relaxation'', while the questions concerning ''how disturbing'' were phrased, ''If you have answered sometimes or often, how disturbing or annoying is it?'' A disturbance score ranging from 0 to 6 was constructed, in which the value for frequency was added to the value for degree of disturbance. A disturbance score >3 was used in evaluating the results. Part 4 of the questionnaire asked about sleep but did not refer to noise. The questions asked about sleep hours, difficulties in falling asleep, how long it takes to fall asleep, awakenings, sleep quality, and tiredness/alertness in the morning. Part 5 of the questionnaire asked about general health, asking how often (''seldom/never'', ''a few times a month'', ''a few times a week'', or ''every day'') subjects experienced various symptoms or signs. Specifically, this section asked how often subjects experienced/felt very tired, headache, stressed, unsociable and preferred to be alone, irritated and angry, stomach discomfort, worried and nervous, and sad and depressed.

4.4. Assessment of sound exposure levels

To link sound exposure and adverse health effects, we attempted to thoroughly document the sound exposure in the study sites. The aim was to assess individual noise immission in spaces potentially relevant to the various studied effects, i.e. outside bedroom, living room, kitchen, balcony, and outdoor relaxation area. Sound levels were determined outside both sides of each dwelling. Assessment of sound exposure levels was based on the following criteria: (1) long-term measurements (for at least one complete week) at representative points in both directly exposed and shielded areas for a representative period (not during holidays or other times when traffic might have been abnormal); (2) short-term measurements (for at least 30 min or 500 vehicles) in a number of complementary positions; and (3) counting of traffic data (number of light and heavy vehicles, and percentage heavy vehicles). When sufficiently exact traffic data were available from authorities, these data were used; and (4) calculations of road traffic noise levels ($L_{\mathrm{Aeq,24h}}$, $L_{\mathrm{night/22\text{-}06/}}$ and L_{Amax}) for each dwelling, based on traffic input and geometrical data for the site (for details of sound exposure assessments, see final report [15] and [16–20]).

4.5. Study material, sound exposure, and form of dwellings

The following four study sites were selected: (1) Johanneberg (JOH), located in the centre of Gothenburg, (2) Björkekärr (BJO), on the periphery of Gothenburg, (3) Hägersten (HAG), a residential area in the outer centre of Stockholm, and (4) Södermalm (SOD), in the inner city of Stockholm. All dwellings in the four study sites were blocks of flats, and 90% of them were in buildings of 3–5 storeys. The speed of the road traffic did not exceed 50 km/h in any of the study sites. The number and type of vehicles were obtained for a 24-h period, and for day (06:00–18:00), evening (18:00–22:00), and night (22:00–06:00) periods. The total number of vehicles, day and night, ranged between 7900 and 11 800 in JOH (heavy vehicles, 395–450), between 7032 and 9924 in HAG (heavy vehicles, 620–659), between 500 and 4000 in SOD (heavy vehicles, 0–300), and between 50 and 200 in BJO (heavy vehicles, 2–8).

The empirical field studies of health effects of road traffic noise were done in spring or autumn, 2000 to 2002. From 2495 households, one individual per household between 18 and 75 years of age was selected for the study. Of these, 870 individuals were omitted (wrong type of dwelling, sick, too brief a residence duration, had moved). Of the remaining 1625 individuals, 956 responded to the questionnaire (59%). The responses revealed that 458 individuals had access to a quiet or shielded section of their dwelling while 498 had no such access. In the latter group, 274 lived in Björkekärr (BJO), Gothenburg, where the dwellings had similar, low sound levels ($L_{\mathrm{Aeq,24h}} = 45$–46 dB, façade reflex included) at both sides.

The mean age of the respondents was 46.1 years (SD 16.1), and 57% were women and 43% men. The mean duration of residence was 10.2 years (SD 11.9).

Table 1 gives the distribution of dwellings (each represented by one individual) in the different sound level exposure categories and study sites. The sound levels at the directly traffic-exposed side are given as free field values. The sound levels at the shielded side and in BJO are given as values including the façade reflex, according to the new calculation model developed in the research programme [17–20]. All sound level values represent the level outside each dwelling; the particular storey was considered in the calculations.

Table 1
Number of respondents and sound levels for the two types of dwellings

Exposure category	Dwellings without access to a quieter side		Dwellings with access to a quieter side			Study sites
	Sound level in $L_{Aeq,24h}$ at both sides of the dwelling (mean, SD)	Number of respondents	Sound level in $L_{Aeq,24h}$ at the directly exposed side (mean, SD)	Sound level in $L_{Aeq,24h}$ at the shielded, quieter side (mean, SD)	Number of respondents	Residential sites and number of respondents
63–68	64.4 1.6	40	64.0 1.3	48.6 1.1	146	HAG (100), JOH (82), SOD (4)
58–62	60.2 1.2	125	60.5 1.2	48.8 1.7	278	JOH (112), SOD(109), HAG (92)
53–57	55.7 1.3	54	55.3 1.7	49.1 0.9	18	SOD (32), HAG (27), JOH (13)
48–52	51.6 0.9	5	51.7 0.6	48.8 0.7	16	SOD (10), HAG (8), JOH (3)
45–46	45.2 0.4	274	—	—	—	BJO (274)

The initial intention was to study a similar number of individuals in each of the two types of dwellings for each sound level category. We were unable to achieve this, since the final assessed sound levels deviated from the sound levels calculated when the study sites were selected. Therefore, some exposure categories include more individuals than others.

BJO, the study site with the lowest sound exposure, was chosen to represent two sound exposure categories in both types of dwellings (45/45 and 45/35 dB). However, the final sound measurements and calculations revealed that the sound levels were mainly determined by noise from a distant highway (E 20) and that sounds from local roads added very little to the noise exposure. Since the sound levels were similar at both sides of the dwellings ($L_{Aeq,24h} = 45$–46 dB at 2 m from the facade) in BJO, only one type of dwelling and one exposure category could be obtained. As seen in Table 1, there were a few individuals in the 48–52-dB category; nevertheless, we decided not to choose another study site to represent this category. The few individuals in the 48–52-dB category lived some distance from the road or in dwellings in the highest storeys.

Maximum sound levels varied in the different sound exposure categories, ranging between L_{Amax} 80 and 83 dB in the three lowest categories and between L_{Amax} 80 and 88 dB in the two highest categories. L_{night} and $L_{Aeq,24h}$ were highly correlated (Pearson correlation coefficient, $r = 0.99$). The difference in sound level between the two metrics varied between 4 and 8 dB, but was generally 6–8 dB. The correlation between L_{Amax} and the other noise metrics was lower ($r = 0.56$ with L_{night} and $r = 0.54$ with $L_{Aeq,24h}$).

The windows were either double-or triple-glazed. Double-glazed windows were more frequent in the two study areas in Stockholm (HAG and SOD). There were no significant differences in annoyance between individuals who had double- vs. triple-glazed windows in their living room and bedroom. Definite conclusions as to the noise-insulating quality of the different types of windows could not be drawn as no measurements were performed. However, other studies suggest that double glazing gives a somewhat lower average noise reduction (R'45°, w $\approx$ 28 dB) than do various types of triple-glazed windows (R'45°, $w = 34$ dB) [21].

Table 2 shows the positions of the rooms, balconies, and outdoor relaxation spaces in the two types of dwellings.

Most of the dwellings ($n = 597$) had living room windows facing the most road traffic-exposed side. In only 85 cases living room windows faced the quieter side, while bedroom windows faced the quieter side in 260 cases. Kitchens were orientated towards the shielded, quieter, and most traffic-exposed sides to similar extents in the four highest sound exposure categories. About 33% of the dwellings had no balcony; a few dwellings (not in table) had two balconies, some having balconies facing both the main and side roads. In these cases, the dwellings were categorized as having a balcony facing the shielded, quieter side. Very few of the dwellings had another outdoor relaxation area to which the residents had exclusive access. About one-third of

Table 2
Position of rooms, balconies, and outdoor areas for relaxation and number of dwellings per exposure category

	Number of dwellings per sound exposure category				
Rooms and other spaces of the dwelling	45–46[a]	48–52	53–57	58–62	63–68
Living room					
Road traffic-exposed side	—	11	70	354	162
Shielded, quieter side	274	10	2	49	24
Kitchen					
Road traffic-exposed side	—	7	30	149	32
Shielded, quieter side	274	6	15	162	57
Not known[b]		8	27	92	100
Bedroom					
Road traffic-exposed side	—	13	62	233	106
Shielded, quieter side	274	8	10	170	80
Balcony					
Road traffic-exposed side	—	2	46	138	67
Shielded, quieter side	272	6	2	117	27
No balcony available	2	13	24	148	92
Common outdoor place for relaxation					
Road traffic-exposed side	—	1	22	29	19
Shielded, quieter side	161	16	20	223	97
No space available	82	4	26	9	59

[a]Site BJO has the same low sound levels at both sides of the dwelling.
[b]No question about kitchen in the first study in HAG.

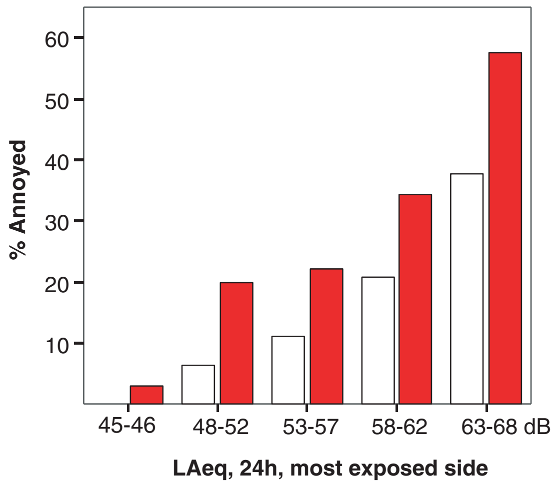

Fig. 2. Percentage annoyed at different sound levels (in $L_{Aeq,24h}$) for individuals without (black bars) and with access to a quiet side of their dwelling (white bars).

the respondents said they had no common outdoor relaxation space, while 20% did not respond to this question.

5. Results

5.1. General annoyance in relation to sound levels and access to a quieter side of the dwelling

The main aim was to determine whether access to a shielded, quieter side of a dwelling has a positive effect on noise annoyance. The results clearly demonstrate the health benefits of having such access. Fig. 2 shows

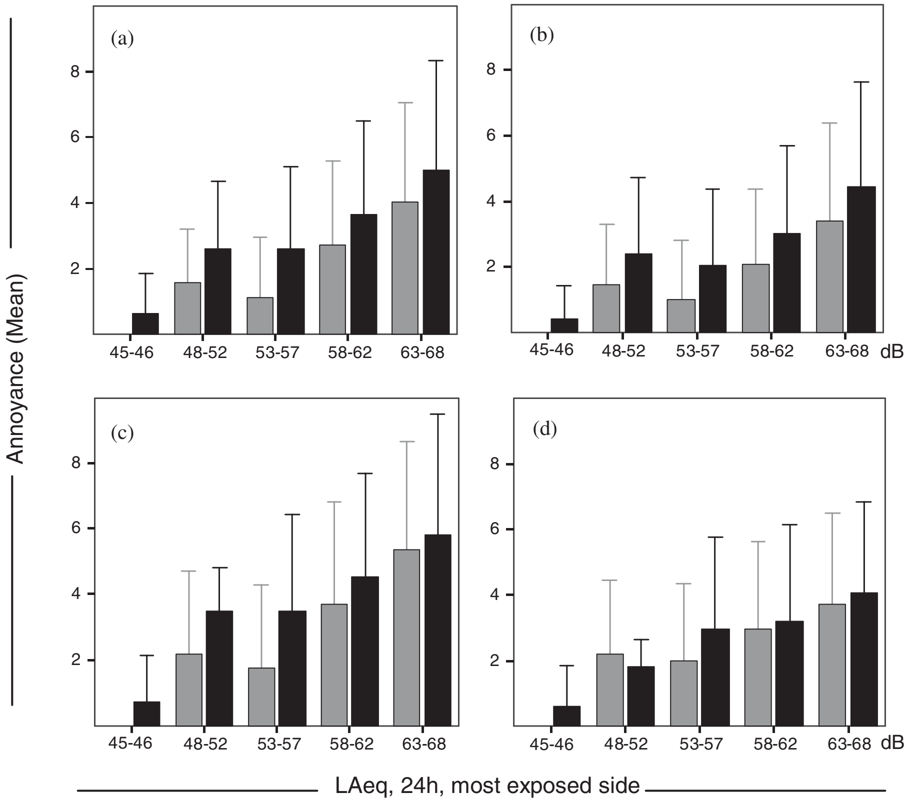

Fig. 3. Mean annoyance scale 0–10 for: (a) at home, (b) indoor, window shut, (c) indoor, window open, and (d) outdoor situations at different sound levels (in $L_{Aeq,24h}$) for individuals without (black bars) and with access to a quiet side of their dwelling (grey bars).

general annoyance assessed using the 5-point category scale (''not at all'' to ''extremely annoyed'') as the percentage of subjects moderately, very, and extremely annoyed at various sound level categories and in relation to type of dwelling. The number of individuals at sound levels between 48 and 52 dB is very small, so the results for this exposure category should be treated with caution.

The percentage of annoyed respondents at 53–57 dB is 11% if there is access to a shielded, quieter side and 22% if there is no such access. At 58–62 dB, the difference in annoyance is 13% (21% versus 34%) between the two types of dwellings, and at 63–68 dB, the difference is 19% (38% versus 57%)—approximately $1^1/_2$ times more annoyed respondents.

Road traffic noise annoyance ''at home'' and in the situations ''indoors with windows closed'', ''indoors with open windows'', and ''outdoors'' was evaluated by the numerical 0–10-point annoyance scales (''not at all annoyed'' to ''extremely annoyed''). The results are shown in Fig. 3.

All the data, except those for the ''outdoor situation'', show a good dose–response relationship between annoyance and sound levels for people both with and without access to a shielded, quieter side of their dwellings. Annoyance ''at home'' is, as expected, higher than ''annoyance indoors with windows closed'' and lower than ''annoyance indoors with open windows''. Notably, annoyance ''indoors with open windows'' is higher than annoyance outside the dwelling. At the two highest sound level categories, the difference in ''outdoors'' annoyance is very small between those with and without access to a quieter side of their dwellings.

5.2. General annoyance, noise sensitivity, and sound levels

The overall relationship (i.e. without considering access to a quiet side) between general annoyance ''at home'' and sound levels ($L_{Aeq,24h}$) at the most-exposed side is shown in Fig. 4.

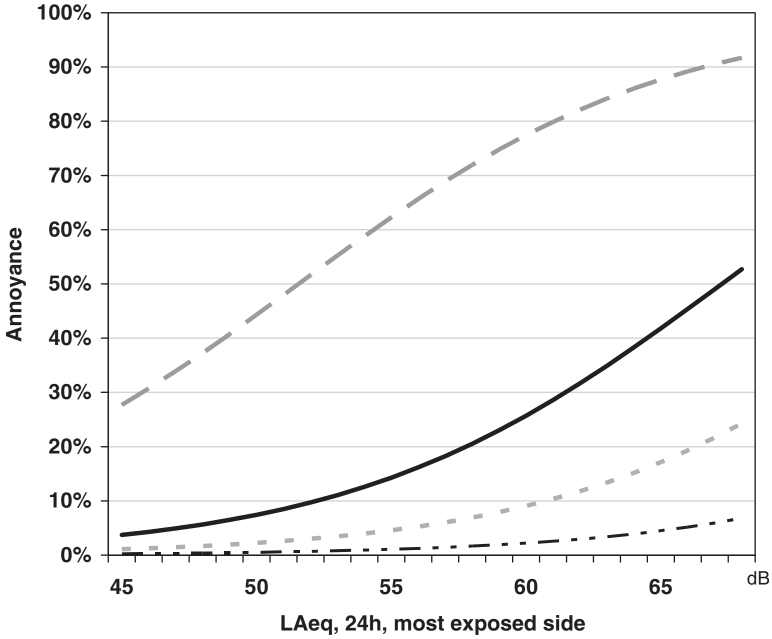

Fig. 4. Relationship between general annoyance (cumulative proportion) for different noise annoyance categories and sound levels in $L_{Aeq,24h}$ at the most-exposed side of the dwelling: – – –, slightly, moderately, very and extremely; ——, moderately, very and extremely; - - - -, very and extremely, – - – -. extremely.

The figure shows a fairly good dose–response relationship between sound level and general annoyance. The solid curve shows that percentage of subjects "moderately", "very", and "extremely" annoyed increased from 3% at 45 dB to 15% at 55 dB, and from 25% at 60 dB to 53% at 68 dB. The dotted curve shows that the percentage of subject "very" and "extremely" annoyed is zero at sound levels around 45 dB, and increased from 4% at 55 dB to 24% at 68 dB.

The relationship (Pearson correlation coefficient, r) between the 1–5 point annoyance scale ("not at all" to "extremely annoyed") and sound levels in terms of $L_{Aeq,24h}$ was $r = 0.47$ ($p < 0.01$). A slightly better correlation was found for the 0–4 point category scale ranging from "don't notice" to "very annoyed" ($r = 0.56$, $p < 0.01$).

Our findings regarding prevalence of noise sensitivity are similar to those concerning other population samples in socio–acoustic surveys. Of the 956 respondents, 18% considered themselves to be not at all sensitive to noise, 46% not very sensitive, 27% rather sensitive, and 9% very sensitive to noise. The relationship between noise sensitivity and the various annoyance scales ranged between $r = 0.34$ (0–4 point scale), $r = 0.36$ (1–5 point scale), and $r = 0.37$ (0–10 point scale). All correlation coefficients were significant at $p < 0.01$. Sound levels were, as expected, not related to noise sensitivity ($r = 0.03$). Fig. 5 presents the annoyance (1–5 point scale) of each of the four noise sensitivity groups as linear regression lines (r^2) in relation to sound levels.

Those who rate themselves as very sensitive to noise are also more annoyed by noise than are the other groups at the same sound levels. However, at the lowest sound levels the difference in annoyance is small but increases with higher sound levels, indicating an interaction effect. The slopes of the regression lines are different for the four groups—the lower the noise sensitivity, the flatter the slope.

5.3. Activity disturbance in relation to sound levels and access to a quiet, shielded side of the dwelling

5.3.1. Disturbance of daytime indoor activities in relation to sound levels

Fig. 6 presents the disturbance of daytime activities with disturbance scores above 3 for the indoor with windows closed situation. A disturbance score above 3 includes individuals who report that they are

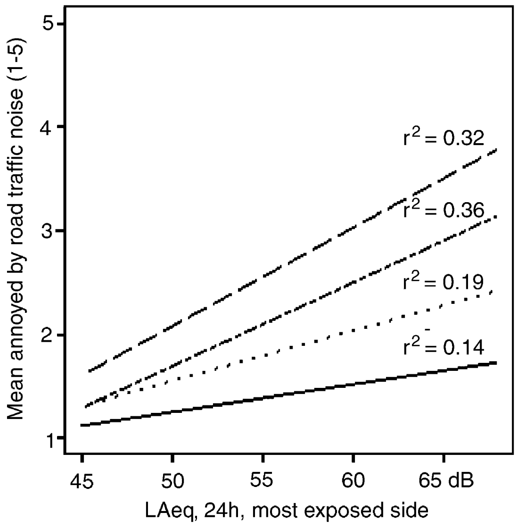

Fig. 5. Relationship between mean annoyance and sound levels in $L_{\mathrm{Aeq,24h}}$; linear regression for subgroups with different noise sensitivities: – – –, very; – - - -, rather, - - - -, not particularly; ——, not at all.

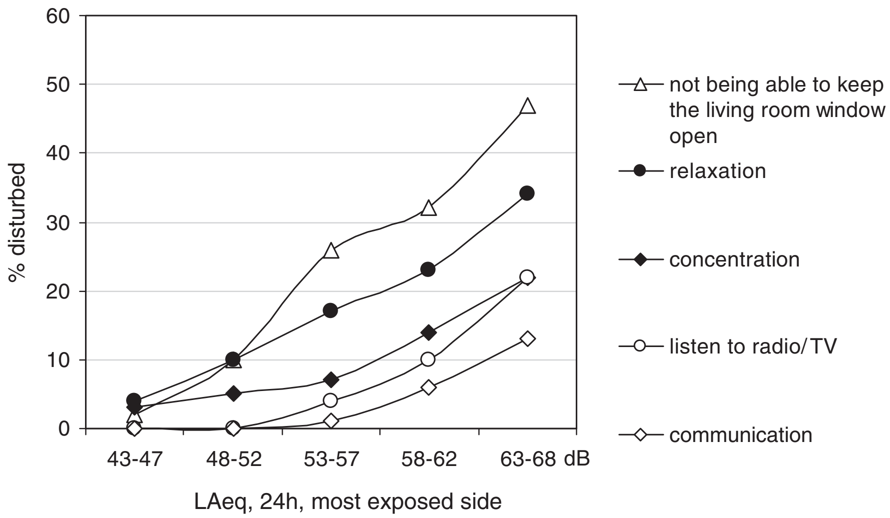

Fig. 6. Activity disturbances (disturbance score >3) indoors with windows closed in relation to sound levels in $L_{\mathrm{Aeq,24h}}$ at the most-exposed side.

"sometimes and rather disturbed" (score 4), "sometimes and very disturbed" (score 5), "often and not very disturbed" (score 4), "often and rather disturbed" (score 5), and "often and very disturbed" (score 6).

Not being able to open the living room windows as often as one wish because of road traffic noise is the most frequent reported disturbance, increasing from 10% at 48–52 dB to 47% at 63–68 dB. This is followed by disturbance of relaxation, concentration, listening to radio/TV, and communication.

Above $L_{\mathrm{Aeq,24h}}$ levels of 53–57 dB, the disturbance curves increase steeply for concentration, listening to radio/TV, and to a lesser degree, for communication. For disturbance of relaxation and not being able to keep windows open, this increase starts at lower levels, i.e. 48–52 dB.

At the highest sound levels the occurrence of disturbed activities generally doubled with windows opened. Table 3 gives the values for daytime activity disturbances with windows closed and the increase in percentage

Table 3
Daytime activity disturbance effects (percentage scoring >3) with windows closed and the increase in disturbance as compared with closed conditions when windows are kept open at different sound levels

$L_{Aeq,24h}$ dB most-exposed side	Communication		Listen to radio or TV		Concentration		Relaxation	
	Closed	Open	Closed	Open	Closed	Open	Closed	Open
45–46	0	+1	0	+2	3	+1	4	+2
48–52	0	+5	0	±0	5	±0	10	±0
53–57	1	+13	4	+13	7	+6	17	+8
58–62	6	+15	10	+19	14	+13	23	+12
63–68	13	+28	22	+24	22	+19	34	+15

disturbed if the windows are opened. The increase in disturbance if windows are opened starts at sound levels of 53–57 dB at the most-exposed side.

Disturbance of communication and listening to radio/TV was less pronounced if windows were kept closed, but with windows opened the increase in percentage disturbed for these activities at the highest sound levels (63–68 dB) is greater than for concentration and relaxation, for which people were already highly disturbed when windows were closed.

5.3.2. Disturbance of daytime activities indoors in relation to access to a quiet shielded side of the dwelling

Daytime activities generally take place in the living room or kitchen; however, in 85 cases only the living room windows faced the shielded, quieter side of the dwelling. Disturbance of daytime activities was thus analysed in relation to whether the dwelling had access to a quieter side or not. The extents of disturbance (disturbance score above 3) of various indoor activities (see Fig. 7) reveal great differences between dwellings with and without access to a shielded, quieter side. If there is no access to a quiet side, the percentage of disturbed respondents increases from 13% to 17% and from 3% to 15% for the sound level categories 63–68 and 58–62 dB, respectively.

5.3.3. Disturbance of outdoor activities and behaviours in relation to sound levels and access to a quieter, shielded side of the dwelling

Noise disturbance of outdoor activities (staying outdoors and opportunities for relaxation) increased at higher sound levels. For subjects whose dwellings *lack* access to a shielded, quieter side, the percentage assigning a disturbance score above 3 to staying outdoors and to relaxation increased from 22% and 26%, respectively, at sound levels of 58–62 dB to 33 and 40%, at the highest sound level category (63–68 dB). For subjects *with* access to a shielded, quieter side of their dwellings, the percentage assigning a disturbance score above 3 to staying outdoors and to relaxation averaged 12% and 21% and 17% and 25% at these same two sound level categories, respectively.

5.4. Health and well-being in relation to sound levels and annoyance

The prevalence of various physiological and psychological symptoms ranged from 8% to 29% in the lowest sound level category (45–46 dB) and from 9% to 46% in the highest sound level category (63–68 dB). The prevalence of symptoms was analysed by dividing the total sample into three sound level categories: *low* sound levels at both sides of the dwelling (45–46 dB), *medium* sound levels (48–52, 53–57, and 58–62 dB), and *high* sound levels (63–68 dB). Table 4 gives the prevalence of symptoms reported daily or weekly in relation to sound levels and access to a shielded, quieter side of the dwelling.

Compared with the quietest area ("Low"), a higher proportion of individuals reported physiological and psychological symptoms daily or weekly in the most sound-exposed areas and whose dwellings lacked access to a quiet side ("High, Noisy"). These differences were statistically significant for the following symptoms: very tired, stressed, unsociable and prefer to be alone, and irritated and angry. There was also a significantly

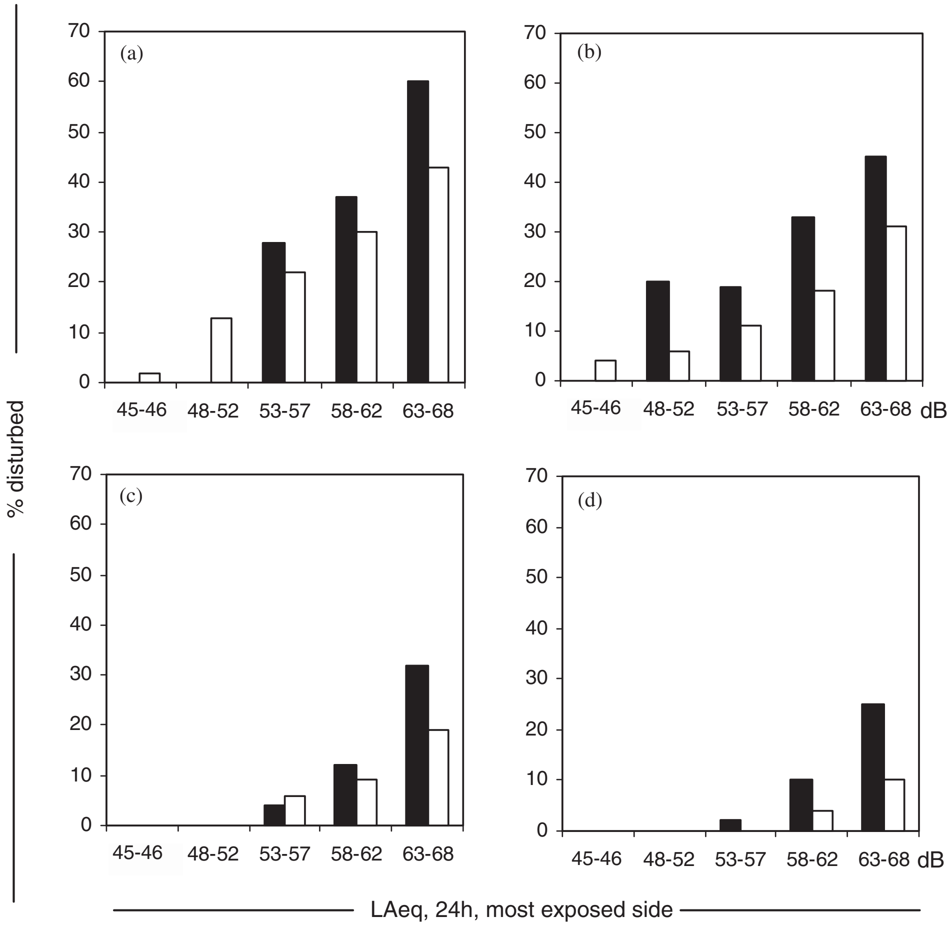

Fig. 7. Activity disturbances (disturbance score >3) indoors with windows closed in relation to sound levels in $L_{Aeq,24h}$ at the most-exposed side for individuals without (black bars) and with access to a quiet side of their dwelling (white bars). (a) Not opening living room windows; (b) relaxation; (c) listening to radio/TV, and (d) communication.

higher prevalence of "unsociable and prefer to be alone" in the most-exposed area ("High, Noisy") than in the medium exposed areas ("Medium, Noisy").

Noise annoyance and disturbed daily activities were related to more frequent physiological and psychological symptoms. The relationships (Spearman correlation coefficient, r_s) between annoyance and the various symptoms were statistically significant ($p<0.01$) for: very tired, $r_s = 0.246$; stressed, $r_s = 0.224$; irritated/angry, $r_s = 0.216$, headaches, $r_s = 0.197$; unsociable, $r_s = 0.191$; sad and depressed, $r_s = 0.181$; stomach discomfort, $r_s = 0.179$; and worried/nervous, $r_s = 0.169$. There were also statistically significant correlations ($p<0.01$) between the various symptoms, and daytime and nighttime disturbances due to road traffic noise. These correlations were similar to those for annoyance and ranged from $r_s = 0.172$ (sad and depressed) to $r_s = 0.240$ (very tired).

5.5. Sleep and sleep disturbances

5.5.1. Sleep behaviour and sleep disturbances

About 10% of the respondents sometimes used *medication* to facilitate sleep, but there was no relationship between this practice and sound levels outside the bedroom windows. About the same number of individuals used *earplugs*, and again, no relationship was found with sound levels. Fig. 8 presents the results for the habit of keeping windows open at night in relation to sound levels in L_{night} ($L_{Aeq,\ 22–06}$) outside the bedroom

Table 4
Physiological and psychological symptoms in relation to sound levels and access to a shielded, quieter side of one's dwelling

	Sound level categories								
Percentage with symptoms every day or a few times a week:	Low[a]	Medium 48–62 dB		High, 63–69 dB		High, noisy versus low		High, noisy versus medium, noisy	
		Quiet[b]	Noisy[c]	Quiet[b]	Noisy[c]		*p*-value		*p*-value
Very tired	29	36	40	36	46	+17	*0.03*	+6	
Stressed	25	37	30	37	43	+18	*0.02*	+13	
Unsociable/prefer to be alone	17	18	19	22	38	+21	*0.002*	+19	*0.008*
Irritated and angry	9	15	18	17	25	+16	*0.003*	+7	
Worried and nervous	13	13	15	18	20	+7		+5	
Sad and depressed	11	13	12	18	18	+8		+6	
Stomach discomfort	8	14	10	15	18	+1		+8	
Suffer from headache	11	11	11	9	13	+2		+2	

[a]Site BJO has no difference in sound levels at the two sides of the dwellings. *p*-values, Mann–Whitney *U*-test, 2-sided test.
[b]Dwellings with a quiet and a noisy side.
[c]Dwellings with no quiet side.

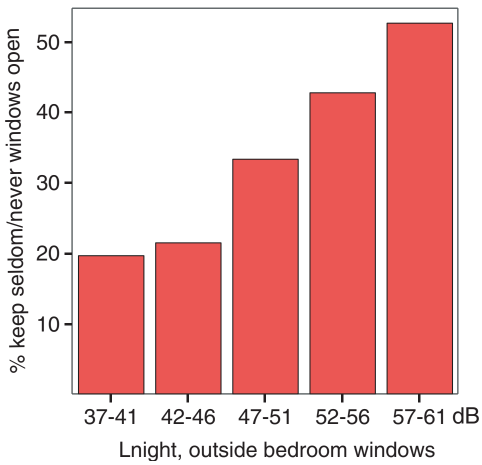

Fig. 8. The habit of keeping bedroom windows open in relation to sound levels in L_{night} outside the bedroom windows.

windows. The percentage of subjects who seldom or never keeps bedroom windows open at night increases from 20% to 53% with higher sound levels outside bedroom windows.

The habit of keeping bedroom windows open or closed at night was also related to *noise annoyance* (Pearson correlation coefficient, $r = 0.23$, $p < 0.01$) and to *noise sensitivity* ($r = 0.13$, $p < 0.01$). Those who were rather or very sensitive to noise kept their windows open less often, a difference of 4–29% in study sites with sound levels above L_{night} 47–51 dB outside the bedroom windows.

Fig. 9 gives the results regarding prevalence of reported noise-induced sleep disturbance assigned scores above 3 for disturbance with windows closed. The sound levels are expressed in L_{night} outside bedroom windows. Not being able to keep bedroom windows open due to road traffic noise was perceived as disturbing

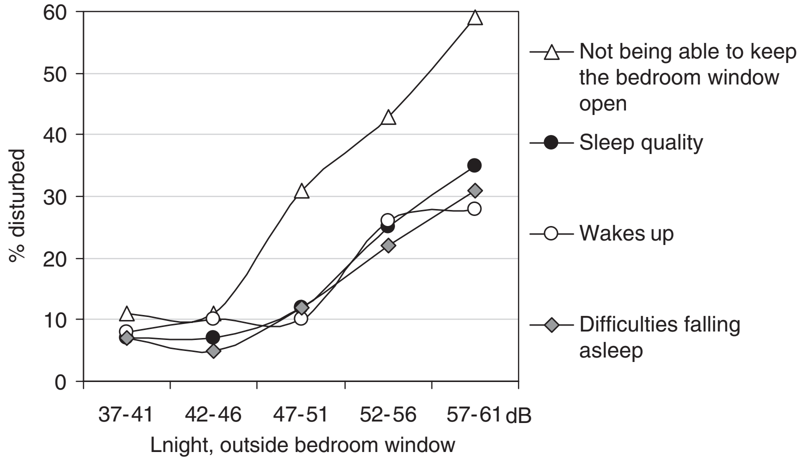

Fig. 9. Noise-related sleep disturbances indoors with windows closed in relation to sound levels in L_{night} outside the bedroom windows.

Table 5
Noise-induced sleep disturbances (percentage scoring >3) with windows closed and the increase in disturbance when windows are open at different sound levels

L_{night} outside bedroom windows	Difficulties in falling asleep		Wakes up		Decreased sleep quality	
	Closed	Open	Closed	Open	Closed	Open
37–41	7	+7	8	+5	7	+5
42–46	5	+6	10	±0	7	+4
47–51	12	+7	10	+5	12	+5
52–56	22	+14	26	+11	25	+11
57–61	31	+10	28	+15	35	+10

by most respondents; this perception increased from 11% at the lowest sound levels to 59% at levels between L_{night} 57 and 61 dB. The three types of disturbed sleep (difficulties in falling asleep, waking up, and disturbance of sleep quality) all displayed a similar dose–response pattern, and the proportion of disturbed subjects increased from 7% to 35% at the highest sound levels. The threshold for the different effects seems to be around L_{night} 47–51 dB outside the bedroom with windows closed. For not being able to keep bedroom windows open the disturbance threshold is lower, around L_{night} 42–46 dB.

The prevalence of the different sleep disturbances with windows open displayed a similar dose–response pattern. Table 5 gives the values for noise-related sleep disturbances with windows closed and open. The frequency of subjects reporting noise-induced sleep disturbances rated above 3 on the disturbance scale increases when windows are kept open; this increase starts even at the lowest sound levels (L_{night} 37–41 dB), while the increase at the two highest sound levels is 10–15%.

5.5.2. Relationship between sleep disturbances and various sound exposure metrics

L_{night} outside bedroom windows correlates better with the different types of sleep disturbances than L_{night} at the most-exposed side. This is shown in Table 6, which presents the correlations between different sound exposure metrics and sleep disturbances with closed vs. open windows. All correlation coefficients in the table are significant at $p<0.01$.

The total nighttime disturbance score (sum of the scores for the separate disturbances) correlates second best with sound levels, after disturbance of not being able to keep bedroom windows open at night. The correlation between the total disturbance score and L_{night} outside the bedroom windows was $r = 0.410$ and the

Table 6
Correlation coefficients (Pearson, r) between sleep disturbances with closed and open windows and different sound exposure metrics

	L_{night} outside bedroom		L_{night} most-exposed side	
Disturbance due to road traffic noise:	Windows closed	Windows open	Windows closed	Windows open
Not opening bedroom window at night	0.460	—	0.338	—
Difficulties in falling asleep	0.287	0.327	0.256	0.319
Wakes up	0.318	0.346	0.244	0.315
Sleep quality	0.314	0.334	0.275	0.320
Total nighttime disturbance	0.410	0.358	0.328	0.339

correlation between total disturbance and L_{night} at the most-exposed side was $r = 0.328$. The correlation coefficients were somewhat higher with open than with closed windows.

Valid L_{Amax} levels could only be obtained outside the most-exposed side, so only bedrooms facing the most-exposed side ($n = 414$) were included in the analysis. The correlations (r) between L_{Amax} and the different disturbances were lower ($r = 0.082$ to $r = 0.126$) than were the correlations between disturbances and L_{night} ($r = 0.190$ to 0.235).

6. Discussion

6.1. Method

To clarify the relationship between acoustic soundscapes including the importance of having access to a quiet side of one's dwelling for various adverse health effects, we selected study sites carefully. The intention was to select one set of five study sites with sound levels ($L_{\text{Aeq,24h}}$) ranging from 45 to 65 dB at both sides (road and courtyard sides) and another set of five study sites with these same sound levels at the most-exposed side (road side) but with approximately 10–20 dB lower sound levels (i.e. 45 dB) at the quieter side (courtyard) of the dwelling [15]. However, this was impossible for all dwellings, as the final assessed sound levels deviated from the levels calculated when the study sites were selected. Thus the 53–57 dB category includes fewer respondents than the 58–62 dB category does. However, the annoyance results for the 53–57 dB category agree well with the exposure–effect curve and are considered reliable.

Although the original preliminary calculations using traditional methods [22] indicated that the quiet sides selected in the field examples (study sites with dwellings having access to a quiet side) had sound levels below $L_{\text{Aeq,24h}} < 45$ dB, free field value, measurements showed that this was not always the case. The actual sound levels in terms of $L_{\text{Aeq,24h}}$ were somewhat higher, averaging 45.8 dB, free field value (or 48.8 dB 2 m from the façade with façade reflex included). The selection criteria were met for the two types of dwellings with and without access to a shielded, quieter side situated along the same street. Compared to other socio–acoustic surveys, which generally only assessed average sound levels at the most traffic noise-exposed side [23–25], the present study conducted a much more detailed assessment of noise immission. Each individual noise immission was assessed in particular spaces relevant to the various studied effects, i.e. outside bedrooms, living rooms, and kitchens as well as on balconies or in outdoor relaxation areas. This systematic approach for studying the adverse health effects and acoustic soundscapes in residential areas has not been applied in previous research. It should be noted, however, that the results obtained are restricted to residential areas without very high road traffic loads, since no dwellings near highways or roads with traffic speeds above 50 km/h were included.

This study does not allow for far-reaching conclusions as to the effects of window insulation on noise annoyance, or as to how annoyed people would have been if their windows facing the noisier side had *very* good sound insulation, i.e. more than 40 dB. Our analysis of annoyance in relation to type of window (double or triple glazed) revealed no association between window type and annoyance at road traffic noise. In a comprehensive review, Fields [26] concluded that there was evidence that noise insulation affected annoyance,

Table 7
Summary of health effects of road traffic noise, benefit of a quiet side, and sound levels[a]

Health effects:	$L_{Aeq,24h}$ both sides	Dwellings *with* a quiet side $L_{Aeq,24h}$ most-exposed side			Dwellings *without* a quiet side $L_{Aeq,24h}$ most-exposed side		
	42–43 dB	55±2 dB	60±2 dB	65±2 dB	55±2 dB	60±2 dB	65±2 dB
General annoyance[b]	3	11	21	38	22	34	57
Relaxation indoor[c] (with windows closed)	4	11	18	31	19	33	45
Relaxation outdoor[d]	3	11	21	25	20	26	40
Sleep disturbances[e] (with windows slightly open)	4	10	17	29	18	34	47
Not able to keep bedroom window open at night	6	10	15	21	34	44	56
Very tired[e,f]	29			36 *+24%*			46 *+58%*
Stressed[e,f]	25			37 *+48%*			43 *+72%*
Unsociable and prefer too be alone[e,f]	17			22 *+29%*			38 *+123%*
Irritated, angry[e,f]	9			*17* *+89%*			25 *+178%*

[a]All dB values in the table are free field values.
[b]Annoyance;% moderately + very + extremely annoyed.
[c]Relaxation and sleep disturbances: % score >3.
[d]Sleep disturbances in columns 2 to 4 include only dwellings where bedrooms face the quiet side.
[e]Symptoms: % every day or few times a week.
[f]Symptoms: +% is the proportional difference compared with prevalence at the quietest site.

although there were some weaknesses in the studies. The National Health Survey in Sweden [4] confirms, however, that "development is definitely not going in the right direction when noise levels in housing of different ages are compared. Residents of housing built after 1985 report disturbance from noise to about the same, or a greater, extent as do residents of housing built between 1961 and 1975" [4, p. 126]. This indicates that houses built after 1985 were either not sufficiently noise-insulated, or were possibly built in more noise-exposed areas.

6.2. Main results

This study gives clear evidence of the health benefits of having access to quiet, noise-shielded indoor and outdoor sections of one's dwelling. Table 7 summarizes our main findings regarding the effects of road traffic noise exposure and access to a quiet section in one's dwelling on noise annoyance, disturbed daily activities, sleep, and physiological and psychological symptoms. Only the quietest site (BJO), which could be referred to as a quiet reference area, and the three highest sound exposure categories are included ($n = 935$) in the table.

Sound levels ($L_{Aeq,24h}$) of 50–55 dB are often considered "acceptable" [1]. These levels are, however, seldom found in today's densely populated city areas. The Swedish long-term goal for 2020 regarding road traffic sound levels is an $L_{Aeq,24h}$ value below 55 dB and an L_{Amax} of 70 dB.This study demonstrates that *even lower* sound levels ($L_{Aeq,24h} < 45$ dB, free field value, at both sides of the dwelling) are required for the sound environment in residential areas to be characterized as "good and healthy". Of the four residential areas, only BJO could be characterized as this, as was supported by the obtained results. Thus, most BJO subjects (97%) were not annoyed by road traffic noise and very few reported disturbance of daily activities or sleep. The occurrence of various psychological and physiological symptoms was furthermore about the same as in a control area with low sound levels below 45 dB, i.e. 11–29% in a previous study [21].

6.2.1. General annoyance

Having access to a quiet side in one's dwelling reduces the proportion of annoyed residents by 11–19% or more, depending on the sound level from road traffic at the most-exposed side of the dwelling. For dwellings with $L_{Aeq,24h}$ levels of 55 dB at *both* sides, the proportion of annoyed residents is the same as for dwellings with $L_{Aeq,24h}$ levels of 60 dB at the most-exposed side but with access to a shielded, quiet side, i.e. 21% and 22%,respectively. Having access to a quiet side in one's dwelling means $1^1/_2$ times fewer annoyed residents at the highest sound levels (65 dB). This represents only a somewhat smaller reduction in annoyance than at lower, 55 dB sound levels, at which there were half the annoyed residents. Considering the influence on annoyance of having access to a quiet side in one's dwelling, it is important that such information be included when new datasets are added to the TNO data archive [27].

The overall analysis, without considering assess to a quiet side, showed that general annoyance measured with the 5-point category scale ranged from 3%to 53% annoyed residents and from 0% to 24% very annoyed residents at sound levels between 45 and 68 dB at the most-exposed facade. These results are similar to the dose–response relationship obtained in the RANCH project [28]. The percentage annoyed was, however, found to be lower at sound levels below 65 dB in the present research (see Fig. 4). For example, we found 10% annoyed residents at $L_{Aeq,24h}$ levels of 52 dB (corresponding to $L_{den} = 55$ dB), compared to 18% in the dose–response curve between transportation noise and annoyance proposed by Miedema and Oudshoorn [27]. A higher percentage annoyed has also been found in other studies [11,21,29]. Öhrström [11] found that 26–40% (depending on the number of noise events above L_{Amax} 80 dB) were *very* annoyed at sound levels between $L_{Aeq,24h} = 60$ and 65 dB, while at higher sound levels (around $L_{Aeq,24h} = 67$ dB) 96% were annoyed and 58% were very annoyed by noise from road traffic [21]. Comprehensive socio–acoustic surveys in Norway involving about 4000 persons [29] show that the percentage of subjects annoyed by road traffic noise ranges between 26% at L_{den} 50 dB and 90% at L_{den} 75 dB. A possible reason for the lower prevalence of noise annoyance found in the present research is that only city areas with relatively low traffic loads travelling at moderate speeds were studied, unlike the studies by Öhrström [11,21]. The inclusion of a high proportion of dwellings with access to a quiet side in the present study might have also contributed to the lower prevalence of annoyance reactions.

It was methodologically interesting that general annoyance, as measured by the numeric 0–10 scale at different locations indoors and outdoors, showed that annoyance "at home" was lower than annoyance "indoors with open windows" but higher than "indoors with windows closed". This indicates that when people are asked about annoyance "at home" they probably give an answer that reflects various contextual factors. Annoyance indoors with open windows was, somewhat unexpectedly, higher than annoyance outdoors close to the dwelling. This could be because people care more about the indoor than the outdoor sound environment. Klaeboe [30] proposes that people's road traffic noise annoyance is modified by the relative quality of their neighbourhood soundscape, defined as the highest sound levels within 75 m of each dwelling. Such a phenomenon probably contributes to the slight difference in annoyance outdoors between residents of dwellings that had access to a shielded, quieter side and residents of dwellings that did not. It might furthermore explain why there was also only a very small difference in annoyance indoors with open windows between the two types of dwellings at the highest sound level categories (63–68 vs. 58–62 dB).

6.2.2. Disturbance of relaxation

The residential soundscape includes places both inside and outside the dwelling, such as balconies and neighbourhood locations for outdoor relaxation [21,30]. Our results confirm that if these places are exposed to road traffic noise, it will have severe effects on people's everyday life and well-being. Whereas traffic noise disturbances of activities involving speech communication seem to be less critical, relaxation activities were considerably more disturbed. For relaxation indoors (with windows closed) and outdoors the benefit of a shielded, quieter side of one's dwelling is between 8% and 15% (corresponding to 1.2 to 1.8 times fewer disturbed subjects) depending on the sound level at the most-exposed side (see Table 7). The benefit of a quiet side is somewhat greater at lower sound levels (55 dB). These findings are in line with those of a longitudinal intervention study conducted before and after changes in road traffic noise [21]. This study found that a substantial decrease in road traffic noise led to a change in people's activities, e.g. they kept their windows open more often and stayed in their gardens to a much greater extent.

6.2.3. Sleep disturbances

Disturbed relaxation and sleep were found to be the most critical effects of exposure to road traffic noise, in line with results of other studies [1,21]. Sleep disturbances were clearly induced by road traffic noise. In particular, difficulties falling asleep, awakenings, decreased sleep quality, and not being able to keep the bedroom window open at night were closely related to sound levels outside bedroom windows, starting at a threshold level of approximately L_{night} 44 dB.This is in accordance with WHO guidelines [1] and implies that only dwellings with bedroom windows facing a quiet side could provide the quietness needed to allow for undisturbed sleep. The benefit of access to a quiet side for sleep ranged between 8% and 18%. Other studies [11,31,32] have also shown that sleep disturbances due to road traffic noise are reported more frequently when bedroom windows face the side of the dwelling directly exposed to traffic noise.

The strong dose–response relationship between sleep disturbance and sound levels found in the present study has not been supported by earlier socio–acoustic field studies, which commonly only examined the sound levels at the most-exposed side of the dwelling. Thus it is known that both L_{Amax} levels and the number of noise events is of greater importance for sleep disturbances than the average sound level (L_{night}) is [33,34]. Unfortunately, no complete analysis could be made of the relationship between L_{Amax} levels, number of noise events, and sleep disturbances due to road traffic noise, since no valid information was available regarding L_{Amax} levels at the quiet side.

6.2.4. Psychological and physiological symptoms

This study provides further evidence that road traffic noise may induce stress-related psychosocial symptoms, and our results are supported by the findings of previous longitudinal studies [10,21]. In areas with high sound levels ($L_{\mathrm{Aeq,24h}} = 65$ dB) and where dwellings offer no access to a quiet side, the prevalence of feeling very tired, stressed, unsociable, and irritated was significantly greater than in the quietest area. Although no dose–response relationship could be found between prevalence of symptoms and sound levels, nonetheless annoyance and activity disturbances (including daytime relaxation and sleep disturbances) were significantly related to the various symptoms. These results fit well with the view that noise is an environmental stressor that causes annoyance and interferes with daily activities, and that over the long term it will induce somatic and psychosomatic symptoms [e.g. 35]. The relationship between traffic noise and stress-related symptoms we found is also supported by the results of other studies (see for e.g. Refs. [36,37]) suggesting a higher prevalence of heart disease in areas exposed to high levels (65–70 dB) of road traffic noise.

6.2.5. Noise sensitivity

Many individuals are sensitive to noise and are vulnerable to its adverse effects. About 1/3 of the present study population considered themselves to be rather or very sensitive to noise, similar to the proportion found in other socio–acoustic surveys [e.g. 21]. Together with sound levels, sensitivity to noise and attitude towards the source are the factors that most strongly influence noise annoyance [21,26,38–41]. The correlation between noise sensitivity and the different annoyance scales we used was relatively high ($r_s = 0.36$), but lower than the correlation between annoyance and sound levels ($r_s = 0.47$). Sound levels from road traffic were not correlated with noise sensitivity. Similar results have been reported earlier by, for example, Ellemeier et al. [38].

7. Conclusions

A *very* good sound environment that promotes health and well-being is one where sound levels from road traffic noise in residential areas are below $L_{\mathrm{Aeq,24h}} = 45$ dB, free field value. Access to quiet indoor and outdoor sections of one's dwelling supports health and results in a lower degree and extent of annoyance, disturbed relaxation and sleep, and contributes to physiological and psychological well-being. The benefit of having access to a quiet side of one's dwelling averages 30–50% for different disturbances, corresponding to a 5-dB reduction in $L_{Aeq,24h}$ levels at the most-exposed side.

To protect most people (80%) from experiencing annoyance and other adverse effects, the sound levels from road traffic should not exceed $L_{Aeq,24h} = 60$ dB at the most-exposed side of one's dwelling, even if there is access to a quiet side (i.e. $L_{Aeq,24h} = 45$ dB free field value or $L_{Aeq,24h} = 48$ dB façade reflection included). A 5-dB lower sound level from road traffic at the most-exposed side (55 dB) protects about 90% of the residents. Thus the "quiet side concept" could help reduce adverse effects of road traffic noise and promote healthier sound environments in residential and other areas, such as schools, preschools, and hospitals. The quiet side concept could be used to reduce adverse effects in "black spots" where sound levels exceed $L_{Aeq,24h} = 65$ dB, by developing shielding (non-residential) buildings. In planning *new* settlements in city areas where sound levels at the roadside do not exceed $L_{Aeq,24h}$ 60 dB, the "quiet side" concept could be applied in creating good, or better, sound environments.

The most sensitive criteria for adverse effects induced by road traffic noise are general annoyance, disturbance of daytime relaxation (indoors and outdoors), and disturbance of sleep with windows slightly open. We suggest that these criteria should be used as indicators in assessing the health impact of road traffic noise.

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