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Railway noise annoyance: Exposure-response relationships and testing a theoretical model by structural equation analysis

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Abstract

In some regions the exposure to railway noise is extremely concentrated, which may lead to high residential annoyance. Nonacoustical factors contribute to these reactions, but there is limited evidence on the interrelations between the nonacoustical factors that influence railway noise annoyance. The aims of the present study were (1) to examine exposure-response relationships between long-term railway noise exposure and annoyance in a region severely affected by railway noise and (2) to determine *a priori* proposed interrelations between nonacoustical factors by structural equation analysis. Residents (n = 320) living close to railway tracks in the Middle Rhine Valley completed a socio-acoustic survey. Individual noise exposure levels were calculated by an acoustical simulation model for this area. The derived exposure-response relationships indicated considerably higher annoyance at the same noise exposure level than would have been predicted by the European Union standard curve, particularly for the night-time period. In the structural equation analysis, 72% of the variance in noise annoyance was explained by the noise exposure (L_{den}) and nonacoustical variables. The model provides insights into several causal mechanisms underlying the formation of railway noise annoyance considering indirect and reciprocal effects. The concern about harmful effects of railway noise and railway traffic, the perceived control and coping capacity, and the individual noise sensitivity were the most important factors that influence noise annoyance. All effects of the nonacoustical factors on annoyance were mediated by the perceived control and coping capacity and additionally proposed indirect effects of the theoretical model were supported by the data.

Keywords: *Annoyance, exposure-response relationship, nonacoustical factors, railway noise, structural equation analysis*

Introduction

Transportation noise is a persisting societal problem that adversely affects people's well-being and health. After sleep disturbance, annoyance is considered as the main burden of disease due to environmental noise in Europe.[1] To assess the number of people annoyed by transportation noise at a given noise level of their dwellings, exposure-response relationships were defined for air, rail, and road traffic noise.[2] These relationships are based on a comprehensive meta-analysis of studies that were conducted >20 years ago.[3,4] Since traffic patterns change with time (e.g., use of other vehicle types, schedules, traffic amount, and composition) and vary locally, studies deriving and complementing exposure-response relationships between transportation noise and annoyance remain necessary. For instance, there are regions that are severely affected by ground transportation noise due to its particular topography. In the Alpine valleys, the direct propagation of the noise from rail and road traffic to the adjacent slopes is assumed to contribute to the high noise annoyance found in this region.[5]

It is generally accepted that any explanation of noise annoyance has to take into account nonacoustical personal and social factors, as well as situational factors. These factors are assumed to explain approximately up to one-third of the variance in annoyance reactions whereas just another third could be attributed to acoustical factors, and the last third of the variance in annoyance is unexplained yet.[6] With respect to situational factors, the time of day when noise events occur is relevant. For railway noise, it was found that annoyance is higher in the evening than during daytime,[7,8] but equally or more prominent during the day

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than in the night-time period.[9,10] There have been a number of studies and reviews identifying critical social and personal nonacoustical factors.[6,11,12] Sociodemographic aspects (e.g., age, gender, education, and social status) prove to be less relevant factors.[11,12] Attitudes, expectations, and beliefs play a major role. Thus, the attitudes toward the source authorities and institutions are relevant which can be dominated either by trust or by "misfeasance with source authorities."[6] An associated concept is the feeling of being fairly treated by noise source authorities. In laboratory studies, it has already been shown that noise annoyance can be diminished through fair procedures[13] and increases by unfair procedures.[14] Furthermore, trust in authorities is related to the expectation how noise will develop in the future, and the belief that noise could be prevented.[6,11] Positive social evaluations of the noise source, for example, the belief of its importance, are deemed to attenuate annoyance.[6,11] On the other hand, fears and concerns increase reported annoyance. Particularly, the role of fear of harm or danger associated with the noise source (e.g., an aircraft crash or a derailing train) as well as the concern about negative health effects of noise itself, have been pointed out.[6,11,12]

Crucial personal factors are the perceived control and coping capacity. These concepts are related to the consideration of noise annoyance as a form of psychological stress[6,15,16] rooted in the stress theory proposed by Lazarus and Launier[17] and laboratory studies by Glass and Singer.[18] According to this conception, stress or annoyance arises from an individual's inability to face a perceived threat (i.e., the perceived disturbance due to noise), also called primary appraisal. The perceived control possibilities (secondary appraisal) determine the degree of evaluating noise as annoying. Psychological stress or annoyance will be higher for lower levels of perceived control.[15] Negative reactions to noise have been found to be better predicted by perceived control than by noise exposure itself.[19] Coping implies any attempt to reduce the negative aspects of stress with the goal to restore a sense of control over a situation.[16] Based on the efficacy of the coping strategy the situation is reappraised (reappraisal). Coping strategies comprise behavioral and cognitive efforts.[20] With respect to noise exposure, behavioral actions include, for example, closing windows or negotiating with people responsible for a noise source and cognitive strategies could manifest, for instance, in maintaining cognitive control by knowing the time schedules of the noise source.[6]

Moreover, the link between annoyance and the individual noise sensitivity is well-established.[21-25] According to Zimmer and Ellermeier[24] noise sensitivity can be characterized as a stable personality trait that covers attitudes toward a whole range of environmental noises. Noise sensitivity is associated to a disposition to negative affectivity,[26] which reflects a tendency to experience discomfort under all circumstances, even in the absence of obvious stress.[27] This finding raises the question whether noise sensitivity represents a specific sensitivity to noise or rather a general negativity. Miedema and Vos[22] concluded that noise sensitivity is more specific. Further, they emphasized that it influences affective/emotional reactions related to environmental conditions, since noise sensitivity was found to predict fear or worry from aircraft. Schreckenberg *et al.*[28] observed an association of noise sensitivity to aircraft noise annoyance and related reactions (perceived pollution and contamination), but not to perceived environmental quality in general. There is evidence that noise sensitivity increases with age and length of residence,[29,30] although not consistently.[23,24] In addition, the concept of noise sensitivity could be reflected in relation to coping/control: "Noise sensitive people …, find noises more threatening and out of their control, and react to, and adapt to noises more slowly than less noise sensitive people" (p. 1).[26]

The relevance of these concepts is mainly examined in their role as moderators between noise exposure and noise annoyance, but the interrelations between these nonacoustical factors have not been completely understood yet. Their specification could provide more insight into the mechanisms that cause the relationship between noise exposure and annoyance. The common practice to study the impact of nonacoustical variables on annoyance is the use of correlational analysis or multiple regression analysis. The first one offers only information about simple associations, but regression analysis is characterized by shortcomings as well, for example, it is not possible to determine indirect and reciprocal effects. In contrast, structural equation modeling (SEM) is a suitable method to examine complex multiple dependence relationships analyzing a series of hypotheses in an entire model. It tests *a priori* theory-driven relationships considering latent variables as well as observed variables. This is not possible by regression analysis. Latent variables refer to hypothetical, not directly observable constructs or factors. These constructs are assumed to be measured only indirectly using observed variables as their indicators (e.g., questions in the survey). This distinction in SEM allows testing a variety of hypotheses about the measurement of constructs and their relationships. The variables can be specified either as predictors and/or as outcome variables.[31] So far, only few approaches used SEM to examine entire models of the interrelation between nonacoustical factors and annoyance due to traffic noise. Taylor[25] used a path-modeling approach examining aircraft noise effects and found that noise sensitivity had the strongest single effect on annoyance. More recently, Kroesen *et al.*[32] presented a comprehensive model for aircraft noise annoyance. Their assumptions are mainly based on the theoretical model by Stallen[15] and the analysis revealed concern about the negative health effects of noise and pollution, perceived disturbance, and perceived control and coping capacity as the most relevant factors causing annoyance. In this model, the role of noise sensitivity, however, remains unclear. With respect to railway noise annoyance, there are some studies using a path modeling approach as well.[33-35] Richardson[33] suggested a causal model with rail noise, belief in noise preventability, happiness with daily lives, concerns about negative health effects of noise, and fear of the noise source as determining factors of noise annoyance. However, models using the SEM approach with a theoretical basis in psychological stress theory still have to be developed and examined for railway noise annoyance, and the present work aims to fill this gap.

The current study had two main objectives. The first goal was the examination of long-term noise annoyance in a region severely affected by railway noise and to establish exposure-response relationships. The second objective was the investigation of the interrelations between nonacoustical factors and annoyance via a structural equation analysis based on a theoretical model of railway noise annoyance.

Theoretical model

The proposed theoretical model for railway noise annoyance [Figure 1] takes psychological stress theory into account and is based on the concepts and findings underlining the role of perceived control and coping capacity.[6,15,16,32] In a cross-sectional survey, the temporal order of these two concepts corresponding to a secondary appraisal and a reappraisal cannot be reflected and is barely separable. It seems reasonable to assume in our theoretical model that subjects' evaluation of perceived control and perceived coping capacity is rooted in a common latent construct. Thus, we included a simplified concept of "perceived control and coping capacity" like in the SEM model of Kroesen *et al*.[32] referring to the perceived resources to face the noise exposure effects.

The perceived control and coping capacity was expected to directly affect the degree of annoyance induced by railway

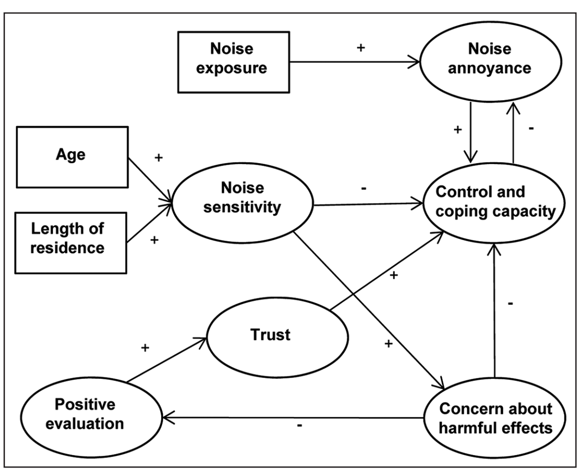

Figure 1: Proposed theoretical model of railway noise annoyance. Arrows indicate the hypothesized causal direction and the signs the expected positive (+) or negative (−) effect

noise. The other nonacoustical factors should exert their effect on annoyance indirectly via coping. Considering that high annoyance in turn can promote the necessity to cope with the noise, a reciprocal effect between annoyance and coping was included in the model.

On the basis of the mentioned previous findings and reviews, it seemed reasonable to include the nonacoustical factors with the most compelling evidence of their impact on annoyance in the model. Hence, the concern about negative health effects of railway noise and the fear of harm from the noise source were included with the expectation that they negatively affect the subjectively perceived coping potential. These variables are supposed to constitute components of a general concern about harmful effects related to the environmental stressor and its source. Trust in noise source authorities should strengthen the perceived control and coping capacity and is proposed as a multifaceted concept. Thus, the latent variable "trust" is expected to include:

a. The perceived fairness,
b. Residents' confidence in the source agents' will to reduce unnecessary noise,
c. The belief that present noise exposure could not be prevented by the noise source authorities, and
d. Residents' expectation that noise will at least not increase in the future.

Positive social evaluation of the source should contribute to a positive attitude toward authorities. Present concerns and fears with respect to noise and source should attenuate this positive evaluation of the source and indirectly influence coping, as well.

In addition, a direct effect of noise sensitivity on perceived coping capacity is assumed. Kroesen *et al.*[32] found that the effect of noise sensitivity on annoyance disappears when the perceived capacity to cope with the noise is included in the analysis. In our model, we hypothesize that perceived coping mediates the effect of noise sensitivity on annoyance since it should be more difficult for noise sensitive persons to use coping strategies and in turn reduce annoyance. A further indirect effect of noise sensitivity on perceived control and coping is proposed via the concern about harmful effects of noise and source. Two directly observable variables were tested, as well. The demographic factors age and length of residence were expected to adversely affect the annoyance via noise sensitivity. In the model of Stallen,[15] noise exposure influences annoyance via perceived short-term disturbance due to noise. General socio-acoustic surveys, however, are usually designed to measure long-term effects (mostly referring to the last 12 months), but not to ascertain short-term disturbance. As supposed for long-term annoyance, ratings of disturbance might be affected by attitudes and beliefs and correlated highly with annoyance ratings. Therefore, the level of disturbance was treated as an aspect of the latent variable noise annoyance.

Methods

Sample and procedure

To collect survey data, a geographical area that is highly exposed to railway traffic noise was selected. The Middle Rhine Valley, an area in Western Germany that is located close to the railway tracks along the river Rhine, is characterized by very high noise levels. The noise situation is exacerbated by the topography of this area.[36] Due to the narrowness of the valley and the historical development, most dwellings of the residential area are located close to the railway tracks and only newer buildings are erected on the slopes. In this region, conflicting interests meet: The economic need for transportation generating both local and transit traffic mainly by the transport of cargo goods versus the need for maintaining residents' quality of life and health as well as preserving the region as cultural heritage and touristic attraction (UNESCO World Heritage since 2002). In recent times, a local protection concept for this area has been started that comprises the development of a railway noise index with the goal to estimate the impact of noise protection measures.[37] In the Middle Rhine Valley, the small town Oberwesel is intensely exposed to noise due to two-tracked railway lines on both sides of the Rhine which are highly frequented by freight train traffic. The current survey was administered in Oberwesel in March and April 2012 and contained questions about noise annoyance due to different types of noise sources, socio-demographic data, and nonacoustical factors. A total of 1457 households, mainly in the old part of the town close to the railway tracks, were approached via a mailshot including an introducing letter and two attached surveys each. Residents could choose between filling in the questionnaire online or offline.

Noise exposure assessment

To assign the noise exposure to the respondents' dwellings, either long-term measurements at each location or a digital noise map according to the European Environmental Noise Directive (END)[38] are required. In contrast to monitoring data, these maps provide area-wide exposure information about noise parameters. The main noise metrics for noise mapping are L_{day}, $L_{evening}$, L_{night}, and L_{den} (day-evening-night). These are long-term averaged sound levels, determined over all the correspondent periods of the year. The daytime periods for the used metrics were defined as follows: L_{day} is the 12 h period from 06:00 to 18:00, L_{night} is the 8 h night-time period from 22:00 to 06:00 and $L_{evening}$ is the 4 h evening time period from 18:00 to 22:00. L_{den} is the weighted average of L_{day}, $L_{evening}$ +5 dB, and L_{night} +10 dB. All of these indicators are defined in terms of A-weighted decibels (dB(A)).

In this study, railway traffic noise was calculated with the model CADNAA version 3.4 (DataKustik, Greifenberg, Germany).[39] The effects of distance from the receiver to the railway line, air absorption, ground properties, topography, and screens were included as major sound propagation effects. The digital elevation map had a special resolution of 10 m. The calculations were done strictly according to the German directive VBUSch[40] which is leaned on the directive "Schall 03"[41] and is adapted to the requirements of the END.[38]

The traffic data and information about the train classes, velocities and train lengths determine the noise emission at a specific railway stretch. To calculate the average noise distribution over a time period of a day or a year, there are no consistent traffic data available. Our aim was to reproduce the results from the noise mapping published by the Federal Railway Authority.[42] Therefore, we made a compromise between the available rough data of 65,000 trains/year from the Federal Railway Authority and observation data from a monitoring station in Oberwesel[43] close to the railway line. At the monitoring station, a high fluctuation of train frequency during the daytime and the week can be observed. In our simulation, the freight train frequency was set to 34 during daytime, 16 in the evening, and 40 during night-time. The trains had a set velocity of 100 km/h and a length of 600 m. The passenger train frequency was set to 82 (day), 18 (evening), and 20 (night) respectively with a set velocity of 180 km/h and a length of 205 m according to Giering and Augustin.[44] Concerning the ballast bed there is added 2 dB according to "Schall 03".[41] From these data an emission level of 74.2 dB (day), 74.8 dB (evening), and 75.2 dB (night) resulted. No other sources except for railway noise were included into the simulation. Finally, the calculated noise levels were validated by comparison with the noise mapping[42] as well as with the long-term noise levels measured at the monitoring station in Oberwesel.[43]

A great advantage of digital noise maps relying on realistic average data is that the noise can be addressed to each respondent's dwelling. According to the END,[38] the building noise level corresponds to the most-exposed façade level and is used as noise metric in the following analysis.

Assessment of annoyance

Long-term annoyance was measured by a 5-point scale ranging from 1 = "not at all annoyed" to 5 = "extremely annoyed" according to ICBEN[45] and ISO standards.[46] "Thinking about the last 12 months, when you are at home, how much does noise from the following noise sources disturb or annoy you?" Respondents were required to evaluate annoyance due to the noise sources rail, road, air, ship traffic, neighbors, construction, and industry. Regarding railway traffic noise, the 11-point scale measuring noise annoyance from 0 = "not at all annoyed" to 10 = "extremely annoyed" was added. Several disturbances of activities by railway noise (relaxation, conversation, sleep, and concentration) as well as noise annoyance at different times of day (day: 06:00-18:00 h, evening: 18:00-22:00 h, night: 22:00-06:00 h) were measured by the 5-point semantic scales. In addition, respondents could indicate more specific time periods when they were particularly annoyed (24 h separated in intervals of 3h). Further scales referred to specific emotional and behavioral reactions to rail noise (e.g., avoiding the use of garden, balcony, terrace; use of tranquilizers or sleeping pills; anger and irritableness) using 5-point semantic scales from 1 = "never" to 5 = "always".

Assessment of nonacoustical factors

Since the SEM approach was used the nonacoustical factors as well as annoyance were considered to be latent variables. Table 1 summarizes the latent variables with the hypothesized associated items of the questionnaire and the range of response format as well as the item label used in the following. The concepts noise sensitivity and perceived control and coping capacity were measured by validated scales. The questionnaire by Weinstein[47] contains multiple 5-point scales to assess noise sensitivity and was used in the short version with six items[48] in the German translation.[49] To assess coping capacity and perceived control the scale "subjective coping capacity toward noise" by Guski *et al*.[50] with six 5-point items was adopted. This scale focuses on cognitive and behavioral efforts and resources to control the individual noise situation. No distinction was made between actually performed coping strategies and potential coping capacity. The other latent constructs were also quantified by multiple indicator variables which were *a priori* assigned to the concepts of the proposed model. All indicator variables were assessed on 5-point Likert-type scales.

Statistical analysis

Descriptive statistics were applied to provide basic information about the noise situation and the resulting noise effects. The percentage of highly annoyed (%HA) was represented by the categories 4 and 5 of the 5-point annoyance scale following the recommendation of the ICBEN.[45] Exposure-response relationships between annoyance and noise level were established by logistic regression analysis. In order to compare the relationship with the curve recommended by the European Union (EU) for the estimation of railway noise annoyance simple exposure response relationships were calculated between the noise levels (L_{den}) and %HA.[2,4] According to this approach high annoyance was defined by the upper 28% of the scale (i.e., categories 4 and 5 of the 5-point scale with a weighting of the category 4 with a weight of 0.4). The complex model including nonacoustical factors was tested by structural equation model using IBM SPSS Amos version 20 (Arbuckle JL. Amos (Version 20.0) [Computer Program]. Chicago: SPSS; 2011, USA). The parameters were estimated based on maximum likelihood estimation. In this software, missing values are completed according to full information maximum likelihood estimation. This algorithm estimates parameters directly from all available data without a preliminary data preparation step.[51] All other statistical

Table 1: Non acoustical factors: Latent concepts and items measured by a questionnaire with label and item range

Latent variable	Item/observed variable	Label	Range
Noise sensitivity	I am easily awakened by noise	NS1	1=disagree-5=agree strongly
	I get used to most noises without much difficulty	NS2*	
	I am good at concentrating no matter what is going on around me	NS3*	
	I find it hard to relax in a place that's noisy	NS4	
	I get mad at people who make noise that keeps me from falling asleep or getting work done	NS5	
	I am sensitive to noise	NS6	
Perceived control and coping capacity	If it is very loud, I just mentally switch off	C1	1=disagree-5=agree strongly
	If it is too loud outside, I simply close the windows, and then I am no longer disturbed	C2	
	I do not hear the noise anymore	C3	
	I know that I can protect myself quite well against noise	C4	
	I have accepted the fact that the noise is here	C5	
	Sometimes, I really feel at the mercy of the noise	C6*	
Concern about harmful effects of noise and source	Do you consider railway noise as harmful to health for residents in general?	Con1	1=disagree-5=agree strongly
	Do you consider railway noise as harmful to your own health?	Con2	
	Do you consider railway traffic as harmful to health for residents?	Con3	
	Do you consider railway traffic as dangerous for residents?	Con4	
Trust in noise source authorities	How much do the responsible authorities/institutions really make an effort to reduce railway noise in your neighborhood?	T1	1=not-5=very
	How much do you feel fairly treated in general by responsible authorities/institutions?	T2	1=strongly decrease-5=strongly increase
	Do you consider railway noise as preventable?	T3*	
	How do you think railway noise will develop in the future?	T4*	
Positive social evaluation of railway traffic	What is your general attitude toward railway traffic?	P1	1=disagree-5=agree strongly
	Do you consider railway traffic in general as economically important?	P2	
	Do you consider railway traffic in general as eco-friendly?	P3	
	Do you consider railway traffic in general as convenient?	P4	

*Questions with reverse coding (recoded from 5 to 1) analyses were performed using the software IBM SPSS Statistics version 20 (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.) except for logistic regression analysis with repeated measurements (software R version 3.0.3 package lme4) (R Core Team. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing; 2014). This analysis was used to account for the within-subject correlation caused by repeated ratings of annoyance for different times of day.

Results

Descriptive results

Sample

A total of 380 respondents from the 1457 households approached originally returned the questionnaire. A total of 60 people had to be excluded from the analysis due to incomplete survey data, living outside the relevant residential area or incalculable acoustical data. Thus, a total of 320 respondents resulted for the statistical analysis. They were aged between 18 and 97 (M = 59.1, SD = 16.7), and 50% of the sample was female. The participants lived between 0.2 and 88.3 years in this residential area (M = 29.7, SD = 21.8).

Noise exposure

The calculated average railway noise exposure was L_{day} = 62.9 dB(A) (SD = 10.2), $L_{evening}$ = 63.8 dB(A) (SD = 10.0), L_{night} = 64.6 dB(A) (SD = 9.7), L_{den} = 70.7 dB(A) (SD = 9.7), and L_{eq24h} = 63.8 dB(A) (SD = 9.9). Table 2 shows the number and percentage of respondents exposed to noise levels (L_{den}) categorized into 5 dB subgroups.

Annoyance and reactions to noise

Descriptive results on noise annoyance show that the examined region in the Middle Rhine Valley is exposed to various noise sources, but railway noise is the predominant noise source [Figure 2]. A total of 64.3% of the residents who participated in the survey reported to be highly annoyed by railway noise (M = 3.68, SD = 1.29), followed by road traffic noise (20.7% HA, M = 2.57, SD = 1.11), air traffic noise (7.0% HA, M = 2.03, SD = 0.95), and ship traffic noise (4.1% HA, M = 1.78, SD = 1.40). With respect to different times of day long-term noise annoyance was most prominent during night-time (56.6% HA, M = 3.43, SD = 1.48) and in the evening (52.6% HA, M = 3.28, SD = 1.35) and less during the day (31.8% HA, M = 2.80, SD = 1.27). A descriptive analysis of more specific periods of time of day showed that more than half of the respondents felt particularly annoyed in the late evening hours (20-23 h, 56.6% during weekdays). The morning (8-11 h during weekdays) was least frequently mentioned as particularly annoying (8.1%).

Railway noise caused a variety of reactions in exposed residents. In Figure 3, the percentage of reactions which were "induced by noise often" or "always" is shown. These include actions considered as behavioral coping strategies, for example, as most often indicated "closing windows". Other reactions involve negative emotional feelings of anger or irritableness. The less frequent reaction referred to the "use of tranquilizers or sleep-inducing drugs", but nevertheless 10% of the respondents reported using them "often" or "always" due to noise.

Exposure-response relationships

The definition of highly annoyed for the logistic regression analysis demonstrated a significant influence of the noise indicator L_{den} on annoyance (P < 0.001). In the calculated range from 44 dB(A) to 90 dB(A) the %HA can be predicted by the following polynomial approximation:

$$\%HA = 3.9906 * 10^2 - 2.1140 * 10 * L_{den} + 3.5587 * 10^{-1} * L_{den}^2 - 1.7649 * 10^{-3} * L_{den}^3$$

Deviations to the original curve were not >1% at the tails of the curves. Figure 4 shows the exposure-response relationship derived from the logistic regression analysis in relation to the EU-curve. At the same noise level (L_{den}) the %HA by railway

Table 2: Number and percentage of respondents exposed to railway noise categories (L_{den})

L_{den} (dB(A))	*n* (%)
40.0-44.9	1 (0.3)
45.0-49.9	5 (1.6)
50.0-54.9	22 (6.9)
55.0-59.9	14 (4.4)
60.0-64.9	36 (11.3)
65.0-69.9	75 (23.4)
70.0-74.9	47 (14.7)
75.0-79.9	39 (12.2)
80.0-84.9	69 (21.6)
85.0-89.9	12 (3.8)

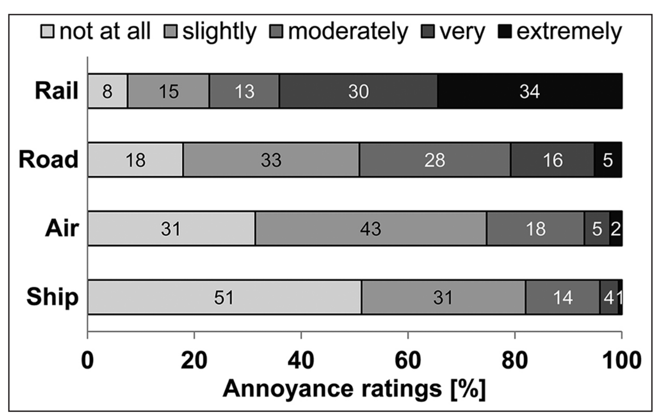

Figure 2: Annoyance ratings due to traffic noise sources in the last 12 months. Percentile distribution of answers to the categories 1 (=not at all annoyed) to 5 (=extremely annoyed)

noise is higher in the examined sample in Oberwesel, Middle Rhine Valley than would have been predicted by the EU-curve. For instance, at a noise level of 70 dB(A) a total of 58% respondents were highly annoyed whereas the EU-curve would predict only 14%.

Furthermore, exposure-response relationships were established for annoyance ratings reported for different times of day. The impact of noise exposure calculated for different times of day (L_{day}, $L_{evening}$, and L_{night}) on the percentage of highly annoyed reported for these periods (day, evening, and night) was analyzed in a single model including the categorical variable "time of day" [Table 3]. The exposure-response relationships based on this logistic regression model as presented in Figure 5 show that at the same noise exposure level railway noise annoyance was lower during the daytime than in the evening and during night-time. For example, at 60 dB(A) the model predicts 14% HA for daytime annoyance, but 36% for the evening, and 39% for the night-time period. This effect is reflected by significant differences between day and evening and between day and night [Table 3], but calculated contrasts showed no significant differences between night and evening ($P = 0.67$).

Interrelations of nonacoustical factors: Results of the structural equation model

The SEM was based on the theoretical assumptions proposed in Figure 1 and the conceptualization of the latent variables summarized in Table 1. The latent variable noise annoyance relied on the 5-point annoyance scale (A1), the 11-point annoyance scale (A2), and the mean level of perceived disturbances (A3). As expected, disturbance correlated highly with the 5-point and 11-point annoyance scales ($r = 0.85$, $r = 0.89$, respectively). It is appropriate to include measurement error correlations when there is sufficient justification.[31] Thus, covariances were added between reversed coded items within a construct (noise sensitivity:

Table 3: Summary of random intercept multivariate logistic regression model predicting the percentage of high annoyance for daytime, evening, and night-time by noise exposure (L_{day}, $L_{evening}$, and L_{night}) and time of day (day, evening, and night)

Variable	β	SE	z	P
Intercept	−10.90	1.05	−10.41	<0.001
Noise exposure	0.15	0.02	9.62	<0.001
Evening	1.25	0.24	5.21	<0.001
Night	1.35	0.24	5.60	<0.001

The factor "time of day" was treated as a categorical factor with "day" as a reference category. SE = Standard error

Table 4: Standardized total effects of the latent variables on annoyance ordered by size

Variable	Effect
Concern about harmful effects of noise and source	0.66
Perceived control and coping capacity	−0.64
Noise sensitivity	0.59
Noise exposure (L_{den})	0.35
Trust in noise authorities	−0.17
Positive evaluation of the source	−0.08

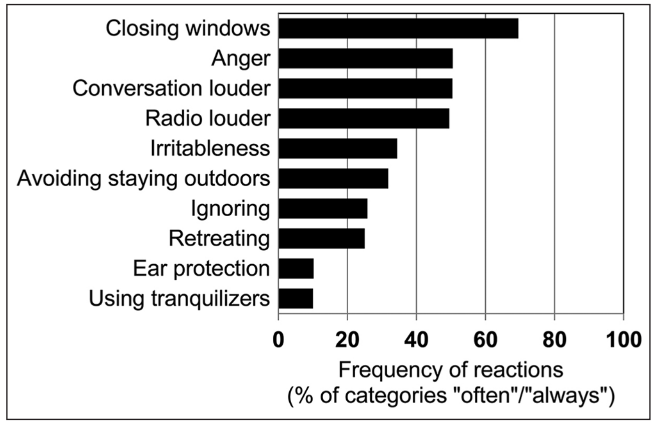

Figure 3: Frequency of reactions caused by railway noise ("How often does railway noise cause the following reactions to you?", percentage of categories 4 = "often" and 5 = "always")

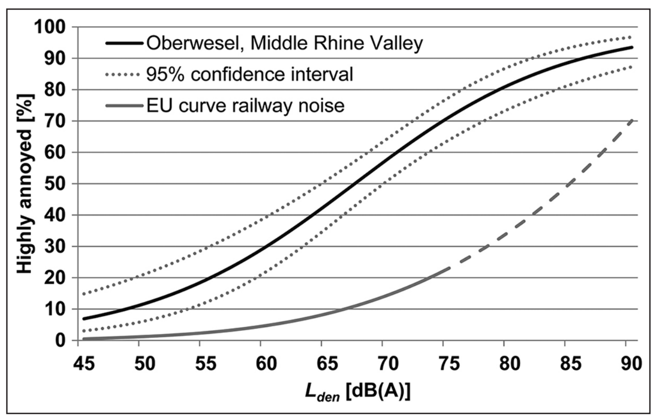

Figure 4: Percentage of highly annoyed by rail traffic noise in the past 12 months as a function of L_{den} compared to the European Union (EU) exposure-response relationship for railway noise.[2,4] The dashed line completes the curve according to the EU formula to the noise levels calculated in the current study

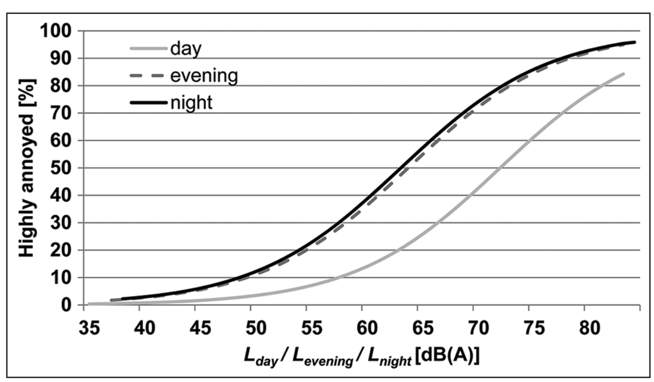

Figure 5: Percentage of highly annoyed persons by rail traffic noise during daytime, in the evening, and during night-time as a function of noise exposure calculations for different times of day (L_{day}, $L_{evening}$, and L_{night})

Items NS2-NS3 and trust: Items T3-T4). In addition, covariances were assumed within the factor perceived control and coping capacity between items that encompass active forms of coping behavior and resulting in beliefs (closing windows [C2], belief to be able to protect oneself [C4], feeling to be at the mercy of noise [C6, reversed item] and items that imply mental forms of coping behavior as a result of a cognitive restructuring process (not hearing the noise anymore [C3], acceptance of the noise [C5], mentally switching off [C1]). According to the coping forms described by Folkman and Lazarus[20] the first group of items is similar to coping forms directing attention toward the problem involving cognitive problem-solving as well as direct action to control the noise. By contrast, the second group of items reflects a shift of attention away from the noise and a change in the subjective meaning of a person-environment relationship by cognitive restructuring. Furthermore, covariances between the items related to fear of the noise source and between general health effects of noise and the source were proposed.

Insignificant paths and items with low multiple r^2 values (<0.20) were removed from the original model (mentally switching off [C1], preventability belief [T3], expectation how noise will develop in the future [T4], age, and length of residence). The final model is shown in Figure 6.

How well this model fits the sample data can be determined by fit indices. The Chi-square was significant ($\chi^2 = 567.61$, df = 260, $P < 0.001$) not indicating a good fit. However,

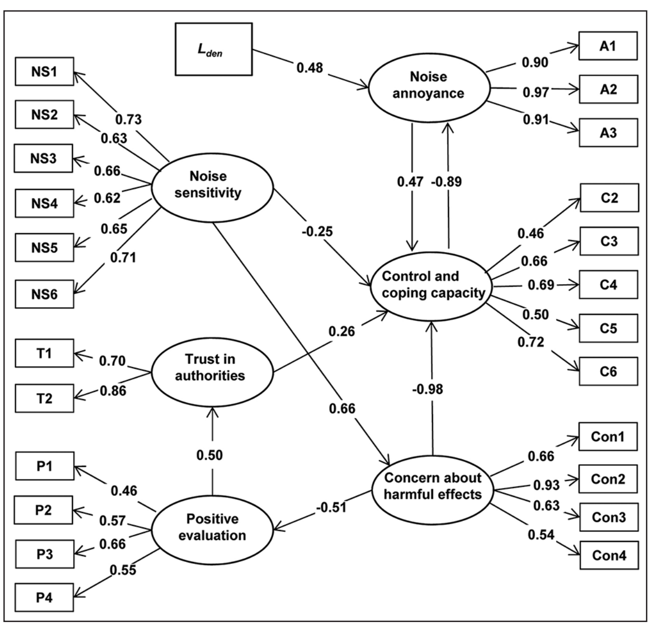

Figure 6: Final structural equation model estimating railway noise annoyance including indirect and reciprocal effects. The values represent standardized path estimates. All parameter estimates are significant (P < 0.01). Item labels of the indicator variables refer to the items of the questionnaire summarized in Table 1. (○) Latent variable, (□) observed variable

there are several shortcomings related to this index (e.g., sensitivity to sample size), and the use of additional indices is recommended.[52] The ratio of χ^2 to df was 2.18 and, therefore, within the bounds between 2 and 3 for an acceptable model fit.[52] The root mean square error of approximation was 0.06 (confidence interval 0.05-0.07) corresponding to the cutoff value for a good fitting model proposed by Hu and Bentler[53] and below the upper limit of 0.07 recommended by Steiger.[54] The comparative fit index was 0.92 and, therefore, above the conventional rule of thumb for a good model fit above 0.90, but below the stringer limit of 0.95 suggested by Hu and Bentler.[53] In recent times, there are concerns about adhering too strictly to these cutoff values and neglect other aspects such as adequacy and interpretability of parameter estimates.[55]

All standardized path estimates of the final model were statistically significant (P < 0.01). The signs of the paths indicated relationships in the hypothesized directions. Hence, noise sensitivity and the concern about harmful effects of noise and source had a direct negative effect on the perceived control and coping capacity. In addition, noise sensitivity influenced coping indirectly via the concern about harmful effects. A direct positive effect of trust in noise source authorities on the perceived control and coping capacity was confirmed as well as an indirect positive effect of a positive evaluation of the noise source via trust. In sum, these three variables (noise sensitivity, concern about harmful effects, and trust in authorities) explained 69% of the variance in the latent variable control and coping capacity. As expected, the level of coping capacity significantly diminished noise annoyance, but the reciprocal effect indicates that the high annoyance foster coping behavior as well. The calculated level of noise exposure (L_{den}) was positively related to noise annoyance. Overall, the acoustical data and the nonacoustical factors together explained 72% of the variance in the central variable annoyance. The size of the single effects on noise annoyance can be ascertained by the standardized total effects which consider both direct paths and indirect effects [Table 4]. The concern about harmful effects of noise and source, the perceived control and coping capacity, and noise sensitivity resulted as the most important determining factors of noise annoyance in the final model. The noise exposure level had a lower impact on annoyance than each of these four nonacoustical variables. Nevertheless, the effect of L_{den} was larger than the total effects of the trust in noise authorities and the positive evaluation of the source.

Discussion

Exposure-response relationships

In the current study, residents living in a German region which is extremely exposed to railway noise completed a socio-acoustic survey regarding their long-term noise annoyance.

The severe exposure can be attributed to rail tracks highly frequented by local and transit traffic with a high proportion of the freight train traffic, and to the specific local topography influencing noise immission. To determine this exposure noise metrics were calculated for the actual address of each responding resident.

With >60% HA respondents this is a much higher proportion than was found in a representative survey of German citizens by the Federal Environment Agency (3% HA).[56] A comparison of the exposure-response relationship obtained in this study with the function recommended for application in European communities[2,4] showed a considerably higher %HA at a given level of noise exposure (L_{den}). This is in agreement with the findings from a larger geographical area of this region[57] and valleys in the Alpine region dominated by rail and road traffic noise.[5] The curves achieved in the present study indicated a %HA in the area that is up to three times higher than defined by the EU-standard curve for railway noise annoyance.

For different times of day, the relationships between the calculated noise exposure and annoyance revealed that residents were higher annoyed during the evening and night-time than during the day at the same noise level. These ratings could be attenuated by the fact that a number of residents might not be at home during the daytime. In this sample, the majority of the residents reported to be usually at home during the daytime (59%). In the evening hours, the need for relaxation and recreation is high, and, therefore, the attention to disturbing sounds and annoyance is higher than during the day.[58] This could be shown for railway noise in other studies.[7,8] The higher annoyance during the night is not in accordance with other studies on railway noise annoyance,[9,10,57] but might be explained in the same way. This period is even more essential for recreation and performance the upcoming day. The noise events in the night are dominated by freight train traffic which has been shown to be more annoying than passenger train traffic.[7,9,59] The data support the penalties applied to the night and evening before combining noise levels to the energy equivalent noise index L_{den} and even higher penalty for the evening than applied at present, since no significant differences between the night-time and evening period were found.

Overall, the exposure-response relationships suggest that the long-term annoyance reaction is very strong in the investigated region. The frequently experienced anger reported by half of the sample points to a strong emotional component of annoyance. Regarding long-term annoyance, it has to be noted that the commonly used noise metric averages noise levels that are subject to fluctuations. Subjective assessments might not be related exclusively to this average, but involve evaluations of particularly noise-exposed periods, single high-maximum noise levels, number of noise events, and other sound characteristics.[6,60] Beyond acoustical factors, the ratings were expected to be highly influenced by nonacoustical factors, because the concept of long-term annoyance reflects an internal representation of the noise situation which is affected by psychological and social factors.[10]

Interrelations between nonacoustical personal and social factors

To examine the interrelations between nonacoustical factors and their effect on annoyance a structural equation model was applied based on predefined theoretical assumptions. The final analysis revealed a plausible model with a good interpretability of its parameter estimates. The model including noise exposure and nonacoustical factors explained 72% of the variance in noise annoyance. This proportion is similar but slightly lower than the explained variance proportion of 78% found for aircraft noise annoyance by Kroesen *et al*.,[32] but corresponds to the suggested approximately two-thirds of the variance that can be explained in total by acoustical and nonacoustical factors according to the rule of thumb.[6] The final model revealed the highest total effects (direct and indirect effects) on annoyance for the concern about harmful effects of noise and source, followed by coping and noise sensitivity. The calculated noise exposure (L_{den}) had a lower effect on annoyance. The smallest total effects on noise annoyance were obtained for the trust in noise authorities and the positive social evaluation of railway traffic. The demographic variables age and length of residence had to be excluded from the model, because the suggested indirect effect on annoyance via noise sensitivity was not achieved.

The strong impact of concern about harmful effects and perceived coping capacity is in line with the results of previous studies.[11,32,33] The present model, however, extends these findings with respect to the role of the personal factor noise sensitivity. In the model by Kroesen *et al.*[32] noise sensitivity had to be excluded probably due to the correlation with perceived control and coping capacity, although the significance of noise sensitivity for explaining noise annoyance is highly stressed.[22,23,25] The hypothesis that the effect of noise sensitivity on annoyance is mediated via the perceived control and coping capacity as well as the concern about harmful effects was confirmed by the results of the current model. It seems reasonable to conclude that noise sensitive individuals focus on the noise, perceive noise events more threatening and are convinced that they cannot control them.[26] As a consequence, they apply neither behavioral nor cognitive strategies to protect themselves against the noise and can hardly adapt to noise. Moreover, high noise sensitivity is related to higher attention to and worry about potential environmental hazards and detrimental health effects. The findings provide evidence for the hypothesis by Miedema and Vos[22] that noise sensitivity influences affective/emotional reactions to environmental conditions such as concerns and fears.

In this model, the concern about negative health effects regarding the noise and the noise source, as well as the perception of railway traffic as dangerous, were confirmed as components of the underlying latent variable (concern about harmful effects of noise and source). The proposed concept of a broader trust variable, however, was not supported by the data. Thus, the expectation that noise will increase in the future, and the preventability belief have to be treated as separate concepts.

The impact of the factors trust and positive social evaluation in the current study was less pronounced than for noise exposure. Nevertheless, these nonacoustical factors were influential and hold potential to be changed by the noise source authorities and institutions. How the responsible agents make their decisions, communicate, allow possibilities for participation, foster positive evaluations of railway traffic and react to conflicts will contribute to the residents' perception of trust and, therefore, their degree of annoyance. In addition, it is important that these authorities and institutions recognize and address existing concerns about harmful effects from the noise and the source as well as personal individual differences and vulnerabilities. The strong impact of noise sensitivity is consistent with previous research and emphasizes that an assumption of all noise-exposed residents being equal and reacting to noise protection measures in the same manner is not acceptable.

The reciprocal effect between annoyance and perceived control and coping capacities as proposed in the stress model by Stallen[15] was verified by the present data and is consistent with the results of an aircraft noise annoyance model.[32] In contrast to the former study, the effect of perceived coping on noise annoyance was larger than vice versa. This finding could be accounted by the complexity of the latent concept coping capacity. Coping can involve direct actions that result in beliefs as well as indirect mental adaptation and control. It seems reasonable that the pathway from annoyance to coping reflects mainly the impact of annoyance on direct control as reactions to acute annoyance (e.g., closing windows). Beyond direct strategies, the inverse direction of the pathway from coping to annoyance could be more attributable to the mental components of coping capacities which prevailed in the coping scale applied in this study. Furthermore, some strategies are useful to reduce temporarily the individual noise exposure, but may involve other negative effects. Especially avoiding coping reactions in contrast to problem-focused strategies could involve negative feelings. Approximately one-third of the subjects reported to avoid frequently staying outdoors and using their garden/terrace and to retreat into quieter rooms. The frequent use of tranquilizers was reported by a lower percentage. These strategies may be problematic since they are considered as a risk factor for negative health outcomes whereas problem-focused coping seems to have a buffer effect between stress and health.[16]

Future theoretical models using the SEM approach could be extended by factors relating to noise exposure (e.g., number of trains, maximum sound pressure levels), further nonacoustical factors (e.g., residential satisfaction) or by physiological measurements (e.g., sleep disturbance, cardiovascular parameters) to elucidate further the mechanisms underlying the association between noise and human health. Several indirect effects have been revealed. For instance, noise annoyance acts as a modifier of the association between noise level and cardiovascular problems[61] as well as between noise level and residential satisfaction.[33,35,62] Furthermore, the relationship between noise sensitivity and health complaints was found to be mediated by perceived stress and sleep problems.[63] Nevertheless, there is no empirically tested unifying model considering indirect and reciprocal effects. In addition, other nonnoise effects of the noise source could be included. In particular, railway traffic is combined with ground-borne vibrations that additionally contribute to residents' annoyance.[34] Another interesting examination would be testing the current or a similar model based on psychological stress theory for road traffic noise annoyance.

Limitations

Although the SEM approach is suited for modeling causal relationships, a confirmation of causality in cross-sectional studies should be considered with caution since the temporal causal order of the associations is not given. The determination of the direction of causality between noise annoyance and psychological factors is difficult, even using panel data that include measurements at two moments in time.[64]

Another limitation of this study stems from the population sample. Data were collected by a survey distributed via mailshot and, therefore, involve the risk of self-selection effects. Hence, the probability that annoyance is overestimated because residents that are not annoyed could have responded less to the survey cannot be ruled out entirely. The use of telephone interviews could avoid this possible bias, but involves other shortcomings due to the exclusion of people who are not available via phone book entries. Nevertheless, even considering a bias, the results underline a much higher annoyance than usually expected in European communities, and that is consistent with other results from this area. Furthermore, the study sample covered a wide range of age, but the mean age of respondents indicates an overrepresentation of older persons. The effect of age, however, resulted not as significant in the present model, suggesting that this possible bias is negligible.

Conclusion

In a German region which is severely exposed to railway noise exacerbated by its specific topography an elevated proportion of highly annoyed residents was found. Exposure-response-relationships showed considerably higher degrees of annoyance at the same noise level as would have been predicted by the EU-standard curve. There is evidence that especially the noise in the night-time period represents a severe problem for the residents. A theoretical model for railway noise annoyance including indirect and reciprocal relationships was supported, and causal interrelations between nonacoustical factors elucidated. The concern about harmful effects from noise and source, the perceived control and coping capacity, and the individual noise sensitivity resulted as the main factors that influence annoyance. The effects of concern and noise sensitivity on annoyance were mediated by the perceived control and coping capacity. In addition, concern of harmful effects mediated the association between noise sensitivity and annoyance.

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