The relation between objective and subjective exposure to traffic noise around two suburban highway viaducts in Ghent: lessons for urban environmental policy

A growing empirical evidence base identifies environmental noise exposure as an important health problem. While the health effects depend for a great part on personal noise sensitivity and contextual factors, in environmental policy generic noise standards and procedures based on objective sound levels are used. In this article the relation between objective and subjective noise exposure variables is further explored by carrying out a residents' survey in a highly noise polluted area along two highways south of the city center of Ghent, Belgium. The survey results show only a weak correlation between objective and subjective exposure variables, with both variables demonstrating different associations with the respondents' background characteristics. While lower-educated and lower-income people are generally higher exposed according to the models, they do not report a higher subjective exposure. People who have been living longer in the area are not necessarily higher exposed according to the models, but do report a higher subjective exposure. Most strikingly, owners of a comfortable detached house report a higher subjective exposure than renters of an apartment or small house, while the latter group is significantly higher exposed according to the models. The results support a plea for the joint evaluation of both objective and subjective noise exposure variables in environmental policy and environmental assessments. In addition, the results argue for specific attention for noise exposure of socio-economically vulnerable people and the establishment of a shared knowledge base on noise exposure with both objective and subjective information.

Keywords: traffic noise; noise exposure; noise annoyance; environmental policy

Introduction

Noise, defined as "unwanted sound", is an increasingly prominent feature of the urban environment and is being seen as an important environmental public health issue (Clark and Stansfeld 2007). Since it is sensed and evaluated by everybody, noise exposure is one of the most frequent complaints of populations living in large cities (Muzet 2007).

The direct auditory effects of noise on humans – like hearing loss – are well established. The corresponding sound levels and effects, however, do not occur in normal urban settings. Non-auditory effects cannot be explained as a consequence of sound energy, but result from noise as a general stressor (Clark and Stansfeld 2007). Babisch (2002) presented a principle stress reaction model with direct and indirect pathways leading to three levels of physiological outcome: stress indicators, biological risk factors and manifest diseases. While stress indicators (associated with annoyance) do not have clinical relevance in se, they can lead to adverse biological reactions (e.g. blood pressure increase) and diseases (e.g. hypertension). However, the pathways from noise exposure to health effects are not straightforward. Several authors have presented conceptual models that point to the influence of mediating and moderating factors on noise-annoyance-health relations (Lercher 1996, Job 1996). The personal psychological reaction of dissatisfaction and annoyance plays a key role in these models, and this is where we start our overview of the evidence on health effects (for another recent overview, see Basner et al. (2014)).

Annoyance is the most reported problem caused by noise exposure and is often the primary outcome used to evaluate the effect of noise on communities (Ouis 2001). Noise annoyance is a feeling of resentment, displeasure, discomfort, dissatisfaction, or offense when noise interferes with someone’s thoughts, feelings or actual activities (Passchier-Vermeer and Passchier 2000). Of all health effects associated with noise, the dose-response relationship between community noise and annoyance is the most developed (Seto et al. 2007). However, researchers agree that, at best, only one third of the variance of annoyance reactions can be “explained” by noise-exposure levels (Guski 1999, Birk et al. 2011). Another third can be explained by personal, social or contextual variables, which leaves one third unexplained. Several authors have tried to reveal the most important moderating variables (Guski 1999, Birk et al. 2011, Kroesen et al. 2008, van Kamp et al. 2004). Personal variables that are often mentioned are noise sensitivity, fear of harm (or health concern), attitude to the noise source and coping capacity. Important social or contextual variables are trust or misfeasance with the source authorities, history of noise exposure and escape possibilities (within or outside the house). Attitude or evaluation of the noise source can also be a shared social variable, with the general attitude towards different kinds of transportation noise a well-known example. Miedema & Oudshoorn (2001) showed that for the same noise levels aircraft noise causes more annoyance than road noise, which in turn is more annoying than railway noise. Stallen (1999) adopted another approach by discerning perceived disturbance from perceived control and stated that is the combination of the two that causes annoyance. In general, it is difficult to distinguish between the different moderating variables since many of them are associated with each other.

Next to annoyance, both objective and subjective evidence suggest a relation between noise exposure and sleep disturbance. Exposure to night-time noise might interfere with the ability to fall asleep, shorten sleep duration, cause awakenings and reduce quality of sleep (Michaud et al. 2007). Sleep disturbance in turn can have an important impact on well-being, causing after-effects during the day: annoyance, irritation, low mood, fatigue, low vigilance and impaired task performance (Stansfeld and Matheson 2003, Muzet 2007). Community studies of traffic noise exposure have found consistent evidence for an effect on sleep disturbance (e.g. Öhrström 2002, Miedema and Vos 2007). Frei et al. (2014) recently found that nocturnal traffic noise has an effect on objective sleep quality, independent of perceived noise annoyance, while the association between self-reported sleep quality and noise is mediated by noise annoyance. This means that the effect of noise exposure on health is dependent on both perceived noise annoyance and unconscious exposure to noise stimuli. Given the effect of chronic noise exposure on annoyance responses and sleep quality, also psychological health might be affected. Studies of adults have confirmed that noise exposure relates to an increase in the number of reported psychological symptoms, such as anxiety and depression, higher levels of psychological distress and a higher prevalence of hyperactivity (e.g. Haines et al. 2001, Stansfeld et al. 1993, Jones et al. 1981, Orban et al. 2016).

There is also consistent and strengthening evidence for a small but significant effect of long-term exposure to transport noise on the somatic effects of hypertension and coronary heart disease. This effect is thought to be the result of stress reactions, and is not necessarily associated with noise annoyance (Clark et al. 2007, Babisch 2006, Münzel et al. 2014). One of the most striking results comes from Jarup et al. (2008), who found an increased risk of hypertension related to long-term aircraft and road traffic noise exposure. Other studies showed an effect of transport noise exposure on the use of anti-hypertensive drugs (Greiser et al. 2007), self-reported hypertension (Rosenlund et al. 2001, Bluhm et al. 2007) and heart attack (Babisch et al. 2005, Selander et al. 2009). Following on from the discussion on confounding of air pollution effects, Gan et al. (2012) found independent effects of traffic-related noise and air pollution on cardiovascular disease and mortality. Also Halonen et al. (2015) adjusted their models for air pollution and found that long-term exposure to road traffic noise was associated with small increased risks of (cardiovascular) mortality, particularly for stroke in the elderly.

This overview shows that a considerable part of the health and well-being effects of noise exposure depends on personal and contextual factors. While there is a direct effect of objective noise exposure on health, which is not fully captured by annoyance, research suggests that subjective exposure variables sometimes explain health effects better than the actual and measured noise levels (Schreckenberg et al. 2010). Several authors concluded that, to assess the public health implications of noise exposure, we need an integrated assessment with both reliable subjective and objective representations of noise exposure (Lercher 1996, Riedel et al. 2014). At the same time, this means that technical interventions reducing noise levels may not have impacts on annoyance and health proportionate to their impacts on sound levels (Laszlo et al. 2012). This idea was confirmed in a review study of Brown and van Kamp (2009), who found no conclusive evidence for a change effect in noise annoyance after the insertion of noise barriers or other mitigation interventions. Noise abatement programs should thus not only focus on the management of sound levels, but also try to reduce annoyance by acting on the social and contextual factors contributing to annoyance (Guski 1999).

To protect environmental health today we dispose of a command-and-control environmental policy with associated norms, regulations, guidelines and procedures for environmental health impacts with indisputable evidence (Verbeek and Boelens 2016). This institutionalized approach of environmental health originated in the 1960s and 1970s, with the establishment of environmental departments and the enforcement of noise standards. Despite the growing empirical evidence on the importance of subjective exposure to noise, environmental health policy still focuses on objective assessments and generic sound level thresholds (binding or guiding). Also the European Union Environmental Noise Directive 2002/49/EC adopted a largely objective approach in the drawing up of "strategic noise maps" and according "action plans". Although the public is consulted in drawing up noise action plans, treating noise annoyance is considered a technical problem that can only be solved by decreasing people's exposure. Even the World Health Organization mainly sticks to objective criteria in their well-acclaimed Guidelines for Community Noise (WHO 1999) and Night Noise Guidelines for Europe (WHO 2009), with L_{de}[1] = 55 dB(A)[2] the recommended threshold for serious

[1] Day-evening equivalent sound level, measured over the 16-hour period 07.00 – 23.00 hours.

[2] A-weighted decibels, expresses the relative loudness of sounds in air as perceived by the human ear.

annoyance in daytime and evening and L_{night}[3] = 40 dB(A) the recommended threshold for sleep disturbance at night.

While the institutionalized environmental health policy undeniably protects a minimum environmental quality for everyone and prevents us from serious environmental problems, it conflicts with the growing emphasis on the moderating effect of personal and contextual factors in explaining the health effect of noise exposure. Treating noise annoyance as a mere technical problem is only one side of addressing the noise problem (Kroesen et al. 2008). Moreover, citizens are increasingly getting aware and concerned about the relation between environmental conditions and possible effects on public health and well-being. In many cases they no longer have confidence in generic environmental regulations, procedures and the available environmental exposure data. Instead they adopt another view on the situation in which they take the specific local context and personal experience into account. The “subjective” perception of environmental impacts by citizens thus interferes with the “objective” assessment of these impacts by the authorities, leading to discussions on the evidence of noise exposure and health effects in actual cases of environmental nuisance.

To more correctly assess the health effects of noise exposure and at the same time better meet citizens’ concerns, it might be a good idea to include subjective aspects of noise exposure in environmental assessments, noise action plans and policymaking. To get more insight into the consequences of this choice, in this article the relation between objective and subjective exposure is further explored in an area with a tangible environmental noise problem and ongoing policy discussions. In this analysis an environmental justice perspective is adopted, using the dimensions of vulnerability and responsibility as defined by Walker (2012),

[3] Night equivalent sound level, measured over the 8-hour period 23.00 – 07.00 hours.

supplemented with a third dimension of residential rootedness.

The concept of vulnerability is approached in terms of how demographic, socio-economic and cultural groups of various forms are more or less vulnerable (Walker and Burningham 2011). Especially socio-economic vulnerability is a critical aspect. Under the same noise conditions, subgroups in socially lower positions may tend to complain less about environmental noise due to habitation to chronic residential noise exposure or adoption of coping strategies (Kohlhuber et al. 2006, Riedel et al. 2014). An approach that focuses too much on annoyance might systematically underrate these population groups' factual exposure, adapt its environmental policy accordingly and enlarge social inequalities. In situations with a social variation in residential noise exposure, this might eventually lead to a mutually reinforcing situation of procedural injustice and distributional injustice (Riedel et al. 2014). What makes it worse is that exposure to pollution is considered to interact with socio-economic vulnerability, producing a "triple jeopardy" of low socio-economic position, polluted environment and impaired health. This means that groups with a lower socio-economic position that already experience a compromised health status due to material deprivation and psychosocial stress, also receive the highest exposure; and this exposure then exerts larger effects on their health than it does on the average of reference population (Pearce et al. 2010, Walker 2012). However, relatively few studies empirically examine socio-economic inequalities in environmental noise exposure and evidence is inconclusive concerning the direction of associations. Several studies show that more deprived populations are subjected to a higher modeled noise exposure (Brainard et al. 2004, Fyhri and Klæboe 2006, Lam and Chung 2012). Nonetheless, studies in the Netherlands and France report that environmental noise exposure levels are highest in middle-class neighborhoods (Havard et al. 2011, Kruize and Bouwman 2004, Bocquier et al. 2013). With regard to annoyance, most studies did not find a clear association of income with noise annoyance (Fyhri and Klæboe

2006, Birk et al. 2011, Fields 1993) but some studies point to high or middle income respondents feeling more annoyed (Michaud et al. 2005, Michaud et al. 2008). Findings on associations with level of education are mixed too. While some authors find that higher educated people feel a little more annoyed (Michaud et al. 2005, Miedema and Vos 1999), most studies find no clear association (Fields 1993, Bluhm et al. 2004, Fyhri and Klæboe 2006, Birk et al. 2011). Finally, for employment status no significant associations with noise annoyance have been found (Miedema and Vos 1999, Fyhri and Klæboe 2006).

With regard to demographic vulnerability the importance of the variables of age and gender has been explored in relation to noise annoyance. In general, no association is found with noise annoyance for gender (Bluhm et al. 2004, Fyhri and Klæboe 2006, Miedema and Vos 1999), but some studies found that women reported more noise annoyance than men (Michaud et al. 2005, Michaud et al. 2008). For age and noise annoyance a curvilinear association was found in the review study of Miedema and Vos (Miedema and Vos 1999), which was later confirmed several times (Michaud et al. 2008, Van Gerven et al. 2009).

The aspect of cultural vulnerability has not been studied much in relation to noise exposure or annoyance. One study that included nationality as an explanatory variable for noise exposure found no clear association (Havard et al. 2011).

As for the responsibility dimension of environmental justice and noise exposure, the most obvious translation of the concept would be a variable that accounts for people’s contribution to the noise problem at hand. With regard to road traffic noise, which is the focus of the case study in this article, a simple proxy indicator that is easily measurable is car ownership. In environmental justice research, the general hypothesis is that poor people are less likely to own a car than wealthier people, contribute less to environmental pollution but suffer disproportionally more often from it (Kohlhuber et al. 2006, Næss 2013). Such an unequal distribution of goods and burdens could be an important argument in environmental justice discussions. However, there is very few research on the association of car ownership with noise exposure or noise annoyance. In the review study of Miedema and Vos (1999), a significant association was found between use of the noise source and annoyance, with more frequent users feeling less annoyed, but it is not clear whether they are also exposed less. For reasons of clarity, the term “car ownership” will be further used to denote this dimension, as it is the only “responsibility” aspect that is examined.

Finally, also residential rootedness can be a matter of environmental justice, since it can be hypothesized that citizens who are more “rooted” in their neighborhood might have higher expectations of their environment and would rather complain or try to change the situation, while they not necessarily bear a higher exposure. Residential rootedness can be translated in variables such as length of residence, ownership, housing typology and single person households (since smaller households are more mobile). Few research is available on this specific topic and results are varied and dependent on context. In a case study in Hong Kong, Lam and Chung (2012) found that renters were generally exposed to higher levels of traffic noise and in a German population based sample, Pollack et al. (2004) found that people living in rented homes more often reported noise annoyance. In their review study, Miedema and Vos (1999) found an association in the other direction, with homeowners feeling more annoyed. Single-person households showed a lower level of noise annoyance in their analysis. Bluhm et al. (2004) found that people living in apartments reported more sleep problems compared to people living in (semi-) detached houses but it was not clear whether they were also higher exposed. Finally, the variable of length of residence has been examined more extensively. For this variable a clear association has been found with health effects, with most evidence on a higher prevalence rate of hypertension for longer exposed individuals (e.g. Babisch et al. 2012, Barregard et al. 2009). Moreover, it is not certain that this relation is mediated by noise annoyance. Most studies do not show an association for length of residence and noise annoyance (Kroesen et al. 2008, Fields 1993, Bluhm et al. 2004, Pierrette et al. 2012, Shepherd et al. 2010), with a notable recent exception of the study of Pennig et al. (2012).

To analyze the relation between objective and subjective exposure using the described environmental justice dimensions, a survey was set up in a specific study area where environmental noise caused by road infrastructure is an issue of policy and societal debate, with different ideas on which data correctly represent the situation. This scale of analysis differs from how Riedel et al. (2014) conceived their study on noise indicators from an environmental justice perspective, using population samples from a larger area.

The study area

The case study concentrates on a highly noise polluted area along two highway routes south of the city center of Ghent (Belgium). Both highways (E17 and B401) have a massive impact on the urban environment, because they consist of two huge viaducts that form a barrier in the suburban tissue and contrast with the predominantly low-rise neighborhoods (Figure 1). The map also shows the boundary of a 500-meter buffer zone at both sides of the highways, where the main environmental impacts have their effect and which is at the core of further analysis. The area is very diverse, ranging from more "urban" neighborhoods in the northwest to more "suburban" neighborhoods in the east, in both socio-economic and housing terms. The map in Figure 1 clearly shows the differences in building density.

Both highways handle a large amount of traffic. According to 2015 numbers, on working days about 120,000 vehicles use the E17 viaduct, and 60,000 use the B401 (cfr. http://www.verkeerscentrum.be for more detailed numbers). With these high traffic intensities, it is not surprising that along the infrastructure lines the levels of environmental noise are relatively high.

[Figure 1 near here]

In recent years both viaducts were at the heart of political debate and the focus of environmental pressure groups. In 2014 a powerful new pressure group was set up that strives for a long term solution for the nuisance of the viaduct and questions the environmental policy of the regional government (administering the roads). This residents group, Viadukaduk, argues that the noise maps do not reflect the annoyance caused by the low-frequent impulse noise produced by the viaduct (http://www.viadukaduk.be). The impulse noise is caused by 192 construction joints which connect 48 parts of the viaduct (a highly unusual construction method). Also the World Health Organization and noise researchers suggest to use separate indicators for impulse noise since the general measurement method underestimates this kind of noise (WHO 1999, Leventhall 2004). This example illustrates the importance of contextual factors in assessing noise annoyance.

Notwithstanding citizens' protest and concern, the public authorities take a defensive position and continue to rely on a fixed environmental regulatory framework based on objective assessments of noise exposure. For example, the Flemish road administration uses an algorithm with arbitrary objective limit values to select priority zones to invest for noise barriers or new road surfaces (Flemish Government 2017). Noise maps form the basis and subjective or contextual aspects are not included. Also the city of Ghent, supporting the residents group but not administering the road, adheres to a structuralist policy framework, by adopting a generic policy target value of L_{den}[4] = 70 dB(A) for all houses (City of Ghent 2014). This value is not based on health evidence, it does not leave room for specific adaptations according to spatial and social context and it does not allow for setting priorities. It is rather a pragmatic, political benchmark instead of an illustration of true concern about the issue of noise exposure. These government policies illustrate the adherence to an objective engineering approach of assessing noise exposure.

Methods

Sampling and survey

The target area for the residents' survey was defined as the zone within 500 meters of the two stretches of the highways E17 and B401 (Figure 1). According to the municipal population register, 15,582 citizens in the age group of 18-79 years live in this zone. The age of majority threshold of 18 years was used to only include respondents that are allowed to vote and to decide themselves where to live, since a part of the survey was on political views and residential choice. People aged 80 and older were excluded because a similar livability survey carried out by the City of Ghent showed a very high non-response in this age group (WES vzw 2014). To reach the standard confidence level of 95% and confidence interval of 5%, at least 375 respondents were needed. As a response rate of about 30 to 40% was expected (based on the survey by the City of Ghent), it was decided to send 1,000 invitations to participate. Because of some rounding of numbers in the sampling, the final number of invitations sent was 1,003. Stratified random sampling was applied, with strata based on

[4] The average equivalent sound level over a 24 hour period, with a 5 dB(A) penalty added for noise during the evening hours of 19:00 to 23:00 and a 10 dB(A) penalty for noise during the nighttime hours of 23:00 to 07:00.

statistical sector[5] and age, to allow for a good spatial and social distribution of invited citizens.

A self-completion ten-page printed questionnaire in Dutch was distributed by mail in February 2016. The questionnaire was addressed to a specific person, and only one person per household could be selected. The respondent was asked to give his personal opinion. The questions were developed in association with Ghent city departments and the local residents group Viadukaduk, and tested in a pilot study with six residents living in the case area. The final questionnaire was accompanied by a two-page official letter, a free return envelope and a multilingual application for receipt of the letter and questionnaire in English, French or Turkish. The participants could also complete the survey online through LimeSurvey software. A minor incentive was provided by way of raffling ten bookshop gift vouchers among the participants.

After three weeks a first reminder was sent. After two months a targeted second reminder was sent to the group of young adults (18-35 years) that was underrepresented in the group of respondents. Seven requests were received for a French version of the questionnaire, seven for an English version and one for a Turkish version. The decision on translations of the questionnaire was only made at that point, and due to financial constraints the questionnaire was only translated in French and English.

Finally, 399 correctly completed questionnaires were returned, corresponding to a response rate of 39.8%. Considering the target of 375 respondents, the scientific requirements of 95% confidence level and 5% confidence interval were met.

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[5] The city of Ghent counts 201 statistical sectors, which have been defined by sociological and spatial characteristics, with an average population of about 1,200 respondents. It is the most detailed level for which census data is available.

To maximize representativeness the correction technique of weighting adjustment was applied in the univariate analysis of results. Since the data could be adjusted for only one variable, it was decided to only correct for statistical sector. In the bivariate analysis of results no weighting was applied.

Subjective measures of noise exposure

The questionnaire included eight pages of questions on environmental health, environmental justice, policy strategies, housing and socio-economic characteristics. Three questions specifically wanted to measure the personal experience of noise exposure, all with a different interpretation:

- **Annoyance**: "In the last 12 months, to what extent have you been annoyed by traffic noise in your neighborhood? *Traffic noise includes both road traffic (including tram) and rail traffic. If you have moved house in the last 12 months, the question only concerns your current neighborhood."* [Answer categories: never – rarely – sometimes – often – always – I don't know)]
- **Relative exposure**: "What do you think about your exposure to traffic noise when you compare it with the average Ghent citizen?" [Answer categories: I have a much lower exposure – I have a lower exposure – I have an equal exposure – I have a higher exposure – I have a much higher exposure – I don't know]
- **Health concerns**: "Are you worried about traffic noise in your neighborhood and the possible effects on your health?" [Answer categories: not at all – rather not – rather yes – definitely yes – I don't know]

Participants background characteristics

The subjective measures of noise exposure are combined with background characteristics of the survey participants. The selected variables for further analysis are divided into five categories: socio-economic vulnerability, demographic vulnerability, cultural vulnerability, car ownership and residential rootedness. The research question is whether in the case area these variables are associated with objective and/or subjective measures of noise exposure. Table 1 lists all variables, with the specific questions and answer categories, and with the operationalization in the data analysis.

[Table 1 near here]

Objective measures of noise exposure

The subjective measures of noise exposure and the background characteristics are compared with objective measures of noise exposure. First, the urban noise maps of the city of Ghent are used, taking road, railway and industry noise[6] into account. These were created for the first time in 2010 following the EU Environmental Noise Directive 2002/49/EC. In 2014, the noise maps were revised by the same consultants AIB-Vinçotte Environment nv and GIM nv (2014). They combined noise measurements with a 3D model containing topography and buildings. They also performed an extensive quality control with model validation on the field. Data are in georeferenced raster format and have a resolution of 10x10m. On the map (Figure 2) and in further analysis, L_{den} (2014) is used as the principal proxy variable for environmental noise. Based on the residential address' exact location, an objective noise exposure value can be linked to each survey respondent.

Second, for every residential address also the nearest distance to the highway is calculated as an objective proximity measure. The assumption is that the proximity or

[6] While technically also industry noise is included in the noise maps, in the case area almost no industrial plants are located. The noise maps thus largely represent road and railway noise.

visibility of the highway might influence the perception of noise exposure (Bangjun et al. 2003).

Statistical analysis

First, univariate results were calculated for the subjective noise exposure variables, yielding representative findings for the case area as a whole. Second, bivariate analyses were carried out between subjective and objective measures of noise exposure, between the different background variables and between the exposure measures and the background variables.

Depending on the type of variables other statistical tests were applied.

- If both variables were continuous or ordinal: Spearman's rank correlation.
- If one of the two variables was ordinal/continuous and the other was binary: Mann-Whitney U test.
- If both variables were binary: Chi Square test.

IBM SPSS Statistics 22 was used to carry out the statistical analysis.

Survey results

Univariate results of subjective noise exposure

First, univariate results for the subjective noise exposure questions are reported. Since statistical requirements were met, results are representative for the population in the study area.

The results in Table 2 show that the majority of the population is at least "sometimes" annoyed by traffic noise, while for 40.6% of the population this is "often" or "always". Table 3 shows how the population in the area assesses its relative exposure. About 43.5% of the population thinks that their exposure is higher than for an average Ghent citizen. A comparable amount of 42.5% of the population is worried about traffic noise exposure and the possible health effects (Table 4). These three measures of subjective noise exposure point to at least a perceived problem of traffic noise pollution in the area.

[Table 2 near here]

[Table 3 near here]

[Table 4 near here]

Relation of subjective exposure with objective measures

In Table 5 three subjective measures of noise exposure are compared on respondent level with two objective measures, i.e. noise exposure according to the modeled noise maps and shortest distance to the highway. The results show a very weak positive correlation between traffic noise annoyance and the modeled (objective) noise exposure (r_s = 0.121*). For the relative exposure measure the correlation coefficient is a little higher (r_s = 0.165**) but for the measure on health concerns no correlation could be found. In general, the modeled noise data are not very good in predicting subjective exposure.

Second, the relation with the proximity measure of shortest distance to the highway was explored, because the presence and visibility of the highway viaducts in people's surroundings might influence their perception of noise. However, the distance to the highway does not play a role in predicting noise annoyance and health concerns. Only the relative exposure to traffic noise is estimated higher when living closer to the highway (r_s = -.151**).

[Table 5 near here]

Associations within background variables

Table 6 shows the results of a correlation analysis of the ordinal background variables. It reveals a strong association between a higher educational level, a higher income, a lower age and a shorter length of residence. A longer length of residence is associated with an older age and a higher probability to live in a more rural housing typology (detached or semi-detached). Remarkably, the number of cars and housing typology are associated with income but not with educational level.

Table 7 shows the results of Mann-Whitney U tests for the combination of binary and ordinal background variables. The results for employment are in line with Table 6, with employed people rather having a higher education, a higher income, a younger age, more cars and a shorter length of residence. Belgians are generally older than foreign origin people, have been living longer in the area and dispose of more cars. House owners are generally older, have been living longer in the area, more often live in a (semi-) detached house, generally have more cars and a higher income. Finally, it turns out living alone in the study area is associated with a lower income, an older age and less chance to own a car.

Table 8 shows the results of Chi-Square tests to evaluate the associations between binary background variables. Three test results are significant. First, it was revealed that unemployed people have a higher chance of living alone (and people living alone having a higher chance of being unemployed). Second, the test results show that men are more likely than women to live alone (and people living alone are more likely to be men). Third, Belgians do much more often own a house (and house owners are much more often Belgians).

[Table 6 near here]

[Table 7 near here]

[Table 8 near here]

Relation of exposure with background variables

Finally, there is looked into the aspects of socio-economic vulnerability, demographic vulnerability, cultural vulnerability, car ownership and residential rootedness, in relation to the distribution of objective and subjective exposure (Table 9 and Table 10).

For the socio-economic vulnerability variables, the results show that socio-economic groups with a higher modeled exposure differ from those with a higher subjective exposure. Following the models, lower educated (r_s = -.185**) and lower income people (r_s = -.242**) are clearly higher exposed to traffic noise. However, this is in general not confirmed by the subjective exposure variables. Only the variable on health concerns shows a significant association with educational level, with less educated people being worried more (r_s = -.131*). For the variable of employment, non-parametric tests show that unemployed people (M = 62.55) are exposed to significantly higher levels of modeled exposure than employed people (M = 60.26), p = .005. Unemployed people are also significantly higher annoyed (M = 3.36) than employed people (M = 3.02), p = .017.

For demographic vulnerability no significant differences in exposure could be found between men and women. With regard to age, a consistent association could be found with older people being exposed a little bit more than younger people, according to modeled exposure (r_s = .108*), annoyance (r_s = .158**) and health concerns (r_s = .129*).

For cultural vulnerability no relation with modeled exposure could be found, nor with annoyance and health concerns. However, estimates for relative exposure are significantly higher among Belgian people (M = 3.41) than among others (M = 2.81), p = .009.

For the car ownership variable "number of cars" remarkable but consistent results could be found. The analysis shows that people who own a car (or more cars) are less exposed according to the models (r_s = -.193**), are less annoyed (r_s = -.123*) and are less worried (r_s = -.123*) about the health effects of traffic noise.

Finally, the relation between exposure variables and residential rootedness was evaluated. A relatively strong correlation was found between housing typology and modeled exposure to noise, with more urban housing typologies (e.g. apartments) being significantly higher exposed than more rural typologies (e.g. detached houses) (r_s = -.413**). However, for subjective exposure an inverse trend is present, with people living in a more rural housing typology feeling more annoyed (r_s = .135**). The results for length of residence are similar but less pronounced. Residents who have been living for a longer period of time in the neighborhood are not necessarily higher exposed according to the models, but they do feel higher annoyed by traffic noise (r_s = .196**) and are also more worried about the health effects (r_s = .143**). Also for the binary variable of ownership remarkable differences are found between objective and subjective exposure. According to the models, renters (M = 62.86) are more exposed than owners (M = 60.19), p = .000, but owners (M = 3.23) report more annoyance than renters (M = 2.92), p = .030. Lastly, while single person households (M = 62.22) are higher exposed than other households (M = 60.32) according to the noise models, they do not report a significantly higher annoyance.

[Table 9 near here]

[Table 10 near here]

Discussion

The results of the survey show that in the case area the relation between perception of environmental impacts and modeled environmental impacts is weak. This means that for the same modeled noise levels the perception of people varies across the whole spectrum from low to high annoyance, with only a weak trend of higher annoyance corresponding to higher modeled exposure. The low correlation coefficients are in line with the literature. It was discussed in the introduction that only one third of the variance of annoyance reactions can be “explained by noise-exposure levels (Guski 1999, Birk et al. 2011) since perception of noise is very dependent on contextual factors and personal sensitivity (Miedema and Oudshoorn 2001, Schreckenberg et al. 2010, Lercher 1996). It can be concluded that modeled noise data are not a good proxy to assess annoyance and (perceived) sleep disturbance.

The survey analysis also showed that the relation with vulnerability, car ownership and residential rootedness variables differs for objective and subjective exposure. The most remarkable contrast was found for residential rootedness. Renters of a small house or apartment, who arrived more recently in the neighborhood, are significantly higher exposed according to model estimates of traffic noise. However, (semi-) detached house owners, who have been living longer in the neighborhood, report more annoyance and are more concerned about health effects. Probably the latter group places higher demands on their residential environment, and because of the longer length of residence, has experienced a firm increase in nuisance. The relation between rental houses and a higher modeled noise exposure is in line with the sparse literature on this topic (Lam and Chung 2012). The higher annoyance levels of house owners are in line with the review study of Miedema and Vos (1999) but in contrast with the findings of Pollack et al. (2004) and Bluhm et al. (2004), who found that renters report more noise annoyance. The relation between length of residence and noise annoyance is usually not found in other studies (e.g. Pierrette et al. 2012, Shepherd et al. 2010), with the study of Pennig et al. (2012) as a notable exception. This again points to the absence of a clear association and the importance of local contextual explanations.

Weaker associations were found for vulnerability and car ownership variables. According to modeled exposure, lower income, less-educated and unemployed people are more exposed. However, these groups do not feel consistently more annoyed. The higher modeled exposure is in line with some previous studies (Brainard et al. 2004, Fyhri and Klæboe 2006, Lam and Chung 2012), but evidence is still inconclusive as other studies show no associations. With regard to noise annoyance, most studies found no significant associations with income, education or employment. The studies that did find an association are in line with our analysis, showing higher income and higher educated respondents feeling a little more annoyed (Michaud et al. 2005, Michaud et al. 2008, Miedema and Vos 1999).

Concerning demographic vulnerability, the absence of an association with gender is in line with most of the literature. For age a small association was found with older people being slightly higher exposed and feeling a little more annoyed. Several authors have pointed to a curvilinear association (Miedema and Vos 1999, Michaud et al. 2008, Van Gerven et al. 2009). By excluding minors younger than 18 years there was partly accounted for this in our study, but more detailed analysis might demonstrate a stronger association.

With regard to the environmental justice aspect of responsibility, operationalized by car ownership, the analysis shows that people without a car are more exposed to traffic noise according to the models, and report a higher annoyance (and more concern about health effects). The relation of car ownership with traffic noise exposure and traffic noise annoyance has not been targeted by many other studies but can provide an important environmental justice argument.

The survey was performed in a stratified random population sample of 399 respondents, leading to representative results for the 15,582 citizens in the age group of 18-79 years living in the study area. The major strength of the study is the combination of different objective and subjective noise exposure parameters in one study, and the assessment of their association with demographic, socio-economic, cultural, residential and car ownership variables. Although the associations are generally weak, they show some consistent trends that ask for further research and policy attention.

This study also has some limitations. First, the results are derived from a single case study and have not been verified in a second case. Since a specific case can have an exceptional outcome attributable to historical, political, economic or social processes (Havard et al. 2011), more cases should be examined to discern the general lessons from the context-specific factors. Second, although the survey results are statistically representative, the sample design inevitably presents some errors (Saris and Gallhofer 2014). The decision to limit the sampling frame to adults between 18 and 79 years old that are listed in the population register excludes certain people, representing a coverage error. The stratified random sampling presents a sampling error, since no form of sampling is neutral and unambiguous. The final step from sample to respondents presents a non-response error, with some groups of the population being over- or underrepresented. A third limitation concerns the objective noise exposure data used in the analysis. Since these data are the result of modeling processes, though starting from measurements and validated by tests on the field, the models remain an estimate of the real situation. Finally, the analysis of associations within the background variables shows relatively high levels of association. By carrying out a multivariate analysis it would be possible to discern the most important predictor variables. However, the aim of our study is not to build an explanatory model, but to demonstrate inequalities in noise exposure and noise annoyance among specific subsets of the population. For this purpose a simple correlation analysis is adequate.

The introductory part of this article discussed the evidence of the health effects of both objective and subjective exposure to traffic noise. While some health effects depend on objective exposure, irrespective of people's perception, many health effects depend for a considerable part on personal noise sensitivity and contextual factors. It therefore seems common sense to include both objective and subjective noise exposure variables in environmental (health) impact assessments of noise exposure. However, in environmental policy a regulatory framework is used with generic noise standards and procedures, based on objective sound levels.

The results described in this article provide additional arguments for changing the way our environmental policy assesses noise exposure. The weak association between objective and subjective exposure variables, and the unequal exposure among different parts of the population, reveal a two-sided story. On the one hand, sticking to only modeling noise exposure is not sufficient, since important situations of noise annoyance and sleep disturbance might be disregarded. On the other, just following citizen's concerns and complaints is also not the right approach, since important environmental inequalities might be ignored. Thus the results support a plea for a combined evaluation of both objective and subjective noise exposure variables in environmental policy and assessments.

Connected to the general advice of using both objective and subjective noise exposure indicators, three additional recommendations are formulated.

First, the shift to more subjective exposure indicators must be performed with caution. Since especially socio-economically more vulnerable people are higher exposed according to the models but do not feel higher annoyed, a too strong shift towards subjective indicators might disadvantage them. It is also these populations that are more susceptible to the negative health impacts, while they often have less choice of residence and contribute less to environmental pollution (by means of private motorized transport). A too strong shift towards subjective indicators might add a procedural injustice to an existing distributional injustice. Therefore, next to subjective exposure, it is worth considering to include aspects of vulnerability (and responsibility) in assessments and policymaking on environmental health issues.

Second, the recognition of the importance of subjective noise exposure opens up opportunities for more creative solutions for noise polluted areas. Thus, interventions should not only be targeted to reducing sound levels but can also try to change people's perception of exposure. Adding more green space, redesigning a neighborhood or just revising noise barrier aesthetics can all have a mediating effect and alleviate noise annoyance. Some empirical studies support these kinds of interventions. The effect of perceived availability of nearby green on noise annoyance was already shown by Li et al. (2010) and Gidlöf-Gunnarsson and Öhrström (2007). Bangjun et al. (2003) showed that the proximity or visibility of the noise source (such as a highway) can influence the perception of noise exposure. Another approach was proposed by Guski (1999). He does not focus on physical interventions, but on the aspect of trust or misfeasance with the source authorities. By providing clear data about the situation, acknowledging the existence of harmful effects and communicating properly, trust could be built which might lower the annoyance. Since perception plays such a big role in all these interventions and because of the valuable local and contextual information citizens can provide, a collaborative approach is most suited to find adaptive solutions.

Third, to treat objective assessments and subjective information equally, a shared knowledge base is needed at project level. This prevents to not get bogged down in discussions on the appropriate data and indicators, which often happens today as our case study showed. At best, a shared knowledge base would banish misinformation and lead to fair and transparent discussions on ethical and normative aspects of policy choices. Following Guski's (1999) ideas (see above) the initiative itself could already lower noise annoyance. To reach a shared knowledge base a transparent dissemination of information is necessary, both within the government and between the government and the public. Open digital platforms should be developed on which different sources of knowledge can be combined and interpreted. These platforms can encourage citizens to gain a broader picture of the situation based on objective top-down information, e.g. to make citizens aware of environmental health effects. In return, their local contextual information and data on noise annoyance should be transferred to the government. It can also be a way for a government to present its data in an understandable way and provide guidance in interpreting the data. As such situational information is connected to objective data and treated equally, opening up the debate and allowing for fairer discussions.

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Tables with captions

Table 1. Participants background variables used in the analysis.

Nr	Variable	Question	Answer categories	Operationalization in analysis
Socio-Economic Vulnerability				
V1	Educational level	What is the highest degree you have obtained?	none or primary education – lower secondary education – higher secondary education – non-university higher education – university higher education	ordinal variable
V2	Income	What is your family's total available monthly income?	less than € 1,000 – between € 1,000 and € 1,999 – between € 2,000 and € 2,999 – between € 3,000 and € 3,999 – between € 4,000 and € 4,999 – more than € 5,000	ordinal variable
V3	Employment	Do you have a paid job at the moment?	yes – no	binary variable: employed/unemployed
Demographic Vulnerability				
V4	Age	What is your year of birth?	[year]	ordinal variable: [year] converted to age
V5	Sex	You are a …	woman – man	binary variable: female/male
Cultural Vulnerability				
V6	Origin	Which nationality did you have at birth?	Belgian – other	binary variable: Belgian/other
Car Ownership				
V7	Number of cars	How many cars does your family have?	none – 1 – 2 – 3 or more	ordinal variable
Residential Rootedness				
V8	Housing typology	Which type of housing do you live in?	studio flat – apartment – single-family row house – single-family semi-detached house – single-family detached house	ordinal variable[7]
V9	Ownership	Do you own or rent your house?	owner – renter	binary variable: owner/renter
V10	Length of residence	Since when do you live in this house?	[year]	ordinal variable: [year] converted to length of residence
V11	Living alone	How many persons live together in the family (yourself included)?	1 – 2 – 3 – 4 – 5 – 6 – 7 or more – I live in a community	binary variable: alone/not alone

[7] While housing typology is in se not an ordinal variable, it was considered ordinal to allow for more profound analysis. With some caution the variable represents a continuum from urban to rural housing typologies.

Table 2. Traffic noise annoyance in case area (cases weighted)

	Traffic noise annoyance	
	Frequency	**Percent**
never	59	*14.8*
rarely	68	*17.0*
sometimes	110	*27.6*
often	97	*24.4*
always	64	*16.2*
I don't know	0	*0.0*
TOTAL VALID	397	*100.0*
No answer	2	
TOTAL	399	

Table 3. Assessment of relative exposure to traffic noise (cases weighted)

	Relative traffic noise exposure	
	Frequency	Percent
I have a much lower exposure	23	*5.7*
I have a lower exposure	49	*12.4*
I have an equal exposure	120	*30.4*
I have a higher exposure	128	*32.3*
I have a much higher exposure	44	*11.2*
I don't know	31	*7.9*
TOTAL VALID	396	*100.0*
No answer	3	
TOTAL	399	

Table 4. Concerns about environmental impact of traffic noise and health effects (cases weighted)

	Environmental health concerns about traffic noise	
	Frequency	Percent
not at all	82	*20.5*
rather not	138	*34.6*
rather yes	144	*36.1*
definitely yes	25	*6.4*
I don't know	10	*2.4*
TOTAL VALID	398	*100.0*
No answer	1	
TOTAL	399	

Table 5. Results for correlation analysis between subjective and objective noise exposure measures

Spearman rank correlation continuous/ordinal variables	**L_{den} total**	**shortest distance to highway**
Traffic noise annoyance	.121*	-.065
Relative exposure to traffic noise	.165**	-.151**
Health concerns about traffic noise	.079	-.049

Table 6. Relation between background variables: correlation analysis

Spearman rank correlation	**(V1)**	**(V2)**	**(V4)**	**(V7)**	**(V8)**	**(V10)**
(V1) Educational level	-	**.357****	**-.342****	.073	-.001	**-.322****
(V2) Income	-	-	**-.292****	**.365****	**.232****	**-.153****
(V4) Age	-	-	-	**-.145****	-.005	**.575****
(V7) Number of cars	-	-	-	-	**.191****	.072
(V8) Housing typology (from studio flat to detached house)	-	-	-	-	-	**.333****
(V10) Length of residence	-	-	-	-	-	-

Table 7. Relation between background variables: Mann-Whitney U tests

Mann-Whitney U test		**(V1) Educational level, M**	**p**	**(V2) Income, M**	**p**	**(V4) Age, M**	**p**	**(V7) Number of cars, M**	**p**	**(V8) Housing typology, M**	**p**	**(V10) Length of residence, M**	**p**
(V3) Employment	employed	**5.15**	**.000**	**3.53**	**.000**	**40.36**	**.000**	**2.02**	**.001**	3.85	.158	**9.85**	**.000**
	unemployed	**4.23**		**2.38**		**59.91**		**1.81**		3.77		**20.85**	
(V5) Sex	female	4.83	.993	3.18	.556	47.27	.925	2.00	.059	3.87	.055	14.39	.304
	male	4.81		3.12		47.05		1.88		3.74		12.56	
(V6) Origin	Belgian	4.84	.555	3.17	.399	**47.76**	**.028**	**1.98**	**.006**	3.84	.063	**14.10**	**.033**
	other	4.59		3.00		**41.03**		**1.68**		3.59		**9.55**	
(V9) Ownership	owner	4.91	.179	**3.28**	**.008**	**49.06**	**.000**	**2.03**	**.000**	**4.03**	**.000**	**16.13**	**.000**
	renter	4.64		**2.89**		**43.32**		**1.79**		**3.36**		**8.46**	
(V11) Living alone	alone	4.77	.606	**2.39**	**.000**	**53.30**	**.000**	**1.66**	**.000**	**3.57**	**.000**	13.26	.992
	not alone	4.85		**3.62**		**43.58**		**2.12**		**3.97**		13.99	

Table 8. Relation between background variables: Chi-Square tests

Chi-Square test		(V3) % employed	p	(V5) % female	p	(V6) % Belgian	p	(V9) % owner	p	(V11) % alone	p
(V3) Employment	employed	-	-	63.2	.960	92.7	.197	68.5	.831	**29.5**	**.000**
	unemployed	-		63.0		88.9		67.4		**52.6**	
(V5) Sex	female	66.0	.960	-	-	90.9	.570	69.7	.439	**32.5**	**.014**
	male	65.8		-		92.5		66.0		**44.9**	
(V6) Origin	Belgian	66.9	.197	62.7	.570	-	-	**71.7**	**.000**	38.4	.087
	other	55.9		67.6		-		**32.4**		23.5	
(V9) Ownership	owner	66.2	.831	64.3	.439	**96.0**	**.000**	-	-	35.7	.355
	renter	65.1		60.3		**81.7**		-		40.5	
(V11) Living alone	alone	**52.0**	**.000**	**55.4**	**.014**	94.6	0.087	65.5	.355	-	-
	not alone	**74.2**		**67.7**		89.6		70.0		-	

Table 9. Results for correlation analysis between noise exposure measures and background characteristics

Spearman rank correlation	Modeled traffic noise L_{den}	Traffic noise annoyance	Relative exposure to traffic noise	Health concerns about traffic noise
Socio-Economic Vulnerability				
Educational level	-.185**	-.068	.024	-.131*
Income	-.242**	-.078	.047	.018
Demographic Vulnerability				
Age	.108*	.158**	.083	.129*
Car Ownership				
Number of cars	-.193**	-.123*	-.076	-.123*
Residential Rootedness				
Housing typology	-.413**	.135**	.057	.101*
Length of residence	-.037	.196**	.026	.143**

Table 10. Results of non-parametric tests for four variables of noise exposure and various background characteristics

Mann-Whitney U test		Modeled traffic noise L_{den} (means)	p	Traffic noise annoyance (scale 1-5) (means)	p	Relative exposure to traffic noise (scale 1-5) (means)	p	Health concerns about traffic noise (scale 1-4) (means)	p
Socio-Economic Vulnerability									
Employment	employed	**60.26**	**.005**	**3.02**	**.017**	3.39	.803	2.28	.313
	unemployed	**62.55**		**3.36**		3.34		2.37	
Demographic Vulnerability									
Sex	female	60.99	.999	3.13	.934	3.34	.475	2.32	.779
	male	61.09		3.14		3.41		2.30	
Cultural Vulnerability									
Origin	Belgian	61.11	.347	3.17	.064	**3.41**	**.009**	2.32	.587
	other	60.08		2.76		**2.81**		2.24	
Residential Rootedness									
Ownership	owner	**60.19**	**.000**	**3.23**	**.030**	3.44	.062	2.35	.260
	renter	**62.86**		**2.92**		3.20		2.25	
Living alone	alone	**62.22**	**.006**	3.16	.818	3.41	.543	2.23	.124
	not alone	**60.32**		3.12		3.34		2.37	

Figure captions

Figure 1. Map of E17/B401 case area with indication of viaduct location

Figure 2. Distribution of average yearly L_{den} total in the case area