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Environmental Inequality in Four European Cities: A Study Combining Household Survey and Geo-Referenced Data

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Abstract

Combining individual-level survey data and geo-referenced administrative noise data for four European cities (Bern, Zurich, Hanover, and Mainz; $n = 7{,}450$), we test the social gradient hypothesis, which states that exposure to residential noise is higher for households in a lower socioeconomic position (measured by income and migration background). In addition, we introduce and test the 'environmental shielding hypothesis', which states that, given environmental 'bads' in the neighbourhood, privileged social groups have better opportunities to shield themselves against them. Our results show that, for many residents of the four cities, observed road traffic and aircraft noise levels are above World Health Organization limits. Estimates of spatial error regression models only partly support the social gradient hypothesis. While we find significant but relatively small income effects and somewhat stronger effects of having a (non-Western) migration background, these effects are not significant in all cities. However, especially high-income households are more capable of avoiding exposure to indoor noise. Due to their residence characteristics and having the resources to maintain high standards of noise protection, these households have more capabilities to shield themselves against environmental bads in their neighbourhood. This supports the environmental shielding hypothesis.

Introduction

While, in the last decades, research on environmental inequality has expanded rapidly in the United States (Mohai, Pellow and Roberts, 2009; Mohai and Saha, 2015a,b), corresponding research in European countries has remained much sparser (Elvers, Gross and Heinrichs, 2008; Laurent, 2011; Preisendörfer, 2014). Early studies on 'the social gradient'[1] of local environmental threats in the European context were mainly conducted by health scientists, epidemiologists, and medical researchers—some of them especially alarmed by the detrimental effects of noise and air pollution on the health and cognitive functioning of children (for a review, see World Health Organization and European Centre for Environment and Health, 2005). It is well known that noise and air pollution, which are often strongly correlated, have an enormous impact on people's health (Basner *et al.*, 2014; European Commission, 2016; European Environmental Agency, 2019). They affect the respiratory and cardiovascular systems and finally lead to increased mortality rates (Forastiere *et al.*, 2007; Qi Gan *et al.*, 2012; Basner *et al.*, 2014). Hence, environmental inequality contributes to the inequality in life expectancy resulting from socioeconomic status and social class. Moreover, the monetary costs of residential environmental bads enhance the 'real' income inequality as measured by the Gini coefficient (Muller, Matthews and Wiltshire-Gordon, 2018).

Social scientists interested in environmental inequality most often examine how local environmental conditions vary according to socioeconomic characteristics and which mechanisms generate their unequal distribution. The typical study on the social gradient is cross-sectional and uses aggregate spatial data at the level of census blocks, communities, or otherwise spatially defined areas. Indicators of socioeconomic status composition and measures of environmental conditions are then simply correlated or analyzed by multivariate regression methods. Few studies use individual-level data, and even fewer use longitudinal individual-level data to investigate the mechanisms presumably generating environmental inequalities (Crowder and Downey, 2010; Pais, Crowder and Downey, 2014; Mohai and Saha, 2015a,b; Best and Rüttenauer, 2018).

In the present study, we do not have longitudinal data and hence cannot uncover causal mechanisms of environmental inequality. However, we can avoid the 'ecological fallacy' that occurs when using aggregate data. The term 'ecological fallacy', originally coined by Robinson (1950), denotes the problem in empirical research that one cannot infer correlations at the individual level from correlations at the aggregate level. A positive correlation between the share of migrants in a district and the district's average level of noise exposure, for example, does not necessarily prove that migrants have to endure more noise than non-migrants. Studies using individual-level data that avoid the problem of a possible ecological fallacy are rare. Where they do exist, the data pertaining to local environmental threats are often based on subjective measures, i.e. perceptions and evaluations of residential environmental conditions by survey respondents (e.g. Best and Rüttenauer, 2018). These subjective measures (noise annoyance, health worries, etc.) may be biased by respondent characteristics, such as education, environmental concern, or—more specifically—noise sensitivity. The main strength of our study is that it combines individual-level survey data with 'objective' data for residential environmental bads, i.e. administrative data on road traffic and aircraft noise. Via geo-referencing, these objective noise data were matched to survey data. Based on the combined survey and 'objective' noise data, we examine social inequalities in the exposure to road traffic and aircraft noise for the Swiss cities of Bern and Zurich and for the German cities of Hanover and Mainz.

Our analyses are guided by two main hypotheses. The first is the social gradient hypothesis, which states that exposure to residential noise is higher for households in a lower socioeconomic position (in our study measured by income and migration background). In addition, we introduce and test a second hypothesis, which we refer to as the 'environmental shielding hypothesis'. This hypothesis states that, if there are environmental bads in the neighbourhood (such as road traffic and aircraft noise), privileged social groups have more and better opportunities to shield themselves against them.

In the 'Theoretical and Empirical Background' section, we discuss these two hypotheses based on findings from previous studies on environmental inequality. The next section then describes our data and methods. In the 'Empirical Results' section, we present descriptive results and estimates from multivariate spatial error regression models (SEM) examining the two hypotheses. The last section draws conclusions.

Theoretical and Empirical Background

The Social Gradient Hypothesis

The basic hypothesis of environmental inequality research suggests a negative correlation between socioeconomic status and unfavourable local environmental conditions (Ringquist, 2005). There are two main processes that might explain this correlation (Mohai and Saha, 2015a; see Rüttenauer, 2018: Chap. 1.2 for an overview). The first process can be termed 'disparate siting' (Mohai and Saha, 2015a) and supposes that investors, politicians, and other decision makers might prefer to locate industrial sites or other unwanted facilities near low-income areas because land and real estate prices are low and other similar facilities are already there. They might also expect less opposition from disadvantaged groups against decisions to locate polluting facilities in their neighbourhood. The second process can be called 'post-siting demographic change' (Mohai and Saha, 2015a) and assumes that low-income groups tend to settle in areas with unfavourable environmental conditions because rents are lower than in less-exposed neighbourhoods. Minority or migrant groups may also experience discrimination in the housing market. This describes a selective move-in process. An additional selective move-out process predicts that privileged social groups have a higher probability of leaving areas with unfavourable environmental conditions.

We cannot test these causal mechanisms in the present study, but we can examine the basic social gradient hypothesis that socioeconomic status matters for exposure to environmental conditions using rather fine-grained, geo-referenced noise data. This is important because, on the one hand, many studies in the United States (for reviews, see Ringquist, 2005; Brulle and Pellow, 2006; Mohai, Pellow and Roberts, 2009; Banzhaf, Ma and Timmins, 2019; for a critical assessment, see Bowen, 2002) and Europe (for Germany, see Mielck and Heinrich, 2002; Best and Rüttenauer, 2018; Rüttenauer, 2018, 2019a; for France, see Padilla *et al.*, 2014; for Switzerland, see Braun-Fahrländer, 2004; Diekmann and Meyer, 2010; for the United Kingdom, see Evans and Kantrowitz, 2002; Mitchell and Dorling, 2003; Agyeman and Evans, 2004; for comparisons of European cities, see Pasetto, Mattioli and Marsili, 2019; Samoli *et al.*, 2019) provide evidence for the existence of a social gradient with respect to social class, income, education, foreign origin, etc. On the other hand, empirical results vary greatly between studies. Evidently, the strength of the association between socioeconomic status and environmental quality can depend on the status dimension (race, income, social class, migration background, etc.), on the type of environmental burden (different kinds of noise and air pollution, distance to landfills, toxic waste, industrial sites, etc.), on the area under study, on the details of area demarcations (the modifiable areal unit problem), and on the statistical methods used.

For example, for French cities, Padilla *et al.* (2014) were puzzled by the seemingly paradoxical phenomenon of a positive social gradient in Paris at the census block level. Air pollution in the French capital (measured by mean concentrations of nitrogen dioxide) is significantly more severe in city blocks populated by people of high socioeconomic status. The reverse, however, is true for the French cities of Marseille and Lille; and in Lyon, the pattern turned out to be curvilinear, i.e. the middle social categories experienced the highest exposure levels. Contrary to common belief among researchers, the 'Paris irregularity' does not seem to be a single exception and the empirical validity of the social gradient hypothesis is far from certain.

In a study pertaining to census blocks in Rome, Forastiere *et al.* (2007) also observed a positive association between exposure to traffic-induced air pollution (measured by particulate matter PM10) and both income and socioeconomic status. Rüttenauer (2019a) explored the association between industrial sites, air pollution, and environmental inequality in German cities (combining data at the city and grid cell level). He found that the burden for foreigners is higher than for German citizens in most cities. However, there are also cities where this relation is reversed. Many cities in Europe and other parts of the world have highly attractive, often historic, and expensive inner-city districts that face serious overcrowding problems accompanied by above-average levels of noise and air pollution. Nevertheless, young professionals and high-income people often prefer an urban lifestyle and therefore choose busy and noisy neighbourhoods located in the inner city. Individual residence decisions are complex, and there is a multitude of factors that people trade off when deciding where to move to and, finally, where to live (Clark *et al.*, 2002; Clark, Deurloo and Dieleman, 2006).

Regarding road traffic noise, one of our explananda, Carrier, Apparicio and Séguin (2016) found slight evidence for the social gradient hypothesis relating to income and minority status based on data from 14 boroughs in Montreal, Canada. In line with the social gradient hypothesis, Casey *et al.* (2017) also document disparities in overall noise pollution (measured at natural/rural sites, urban sites, and near airports) across ethnic and socioeconomic groups at the level of census blocks in the United States. At the city block level, Lagonigro, Martori and Apparicio (2018) report higher noise exposure, including road traffic noise, for unemployed and older people in Barcelona, Spain; yet they do not find differences in noise exposure relating to income and young age (children). Based on data for 201 statistical sectors in Ghent, Belgium, Verbeek (2019) observes a positive association between income and exposure to road, railway, and industry noise.

Contrary to the abovementioned studies, which all refer to aggregate-level data on local environmental disamenities, our approach allows testing the social gradient hypothesis at the individual level, allowing us to avoid the problem of ecological fallacy. Such studies are rare. For example, Diekmann and Meyer (2010) conducted a nationwide survey in Switzerland and linked household data to geo-referenced data on noise and air pollution. Although they found a negative social gradient, the 'slope' was very small in comparison with other factors explaining the variance in exposure to emissions. Living in an urban area rather than in the countryside, for instance, increased air pollution (nitrogen dioxide) by a factor much higher than a hypothetical doubling of income. Swiss census data yielded similar estimates (Diekmann and Meyer, 2017). The authors speculate that the surprisingly weak social gradient may result from Swiss particularities, i.e. the low level of residential segregation, the absence of landfills, and the minimal presence of heavy industry in Switzerland. In the present study, we follow a similar approach focusing on road traffic and aircraft noise.

The Environmental Shielding Hypothesis

Higher exposure to air pollution notwithstanding, Forastiere *et al.* (2007) find in their above-mentioned study about Rome that the negative health effects of air pollution are less pronounced for people with a higher income and socioeconomic status than for those with lower income and socioeconomic status. The authors mainly explain this finding by arguing that low-income and low-status groups are more likely to suffer from chronic diseases (with the strongest differences existing for diabetes mellitus, hypertension, heart failure, and chronic obstructive pulmonary diseases) and are therefore more susceptible to the health effects of air pollution. They further conjecture that rich people are less often outside their residences and frequently have second homes in the countryside. Another possible explanation, which we will follow in our contribution, is the more general assumption that households with a higher level of economic and other resources are more capable of protecting and shielding themselves against environmental bads at their place of residence. We will call this the environmental shielding hypothesis.

'Objective' measures of environmental conditions, such as road traffic and aircraft noise data provided by administrations, usually capture emissions outside a building. However, for a given level of outside noise, inside noise levels can vary greatly. For living comfort, subjective well-being, and health effects, indoor rather than outdoor noise is crucial, and there are more or less effective ways to prevent outside noise from intruding inside a building and thus becoming subjectively annoying. Inspired by psychological stress research (e.g. Aldwin, 2007; Biggs, Brough and Drummond, 2017), we may denote such preventive measures as 'coping strategies'. Whereas coping strategies in stress research typically refer to subjective modes of dealing with stress factors, what we have in mind here are rather 'structural' coping strategies referring to housing characteristics.

A first and very basic factor that enables coping with disturbances originating from outside is a spacious home with several rooms. The more rooms a dwelling has, the higher the chance of having rooms that are less exposed to emissions. This should particularly apply for noise, which we are interested in here, but less so for air pollution. Furthermore, focusing on noise, this rule should also apply more for road traffic than for aircraft noise. If there is residential aircraft noise, it is likely to be uniformly distributed, whereas road traffic may be loud in front of a building and much less so behind it. For our empirical analyses, we expect that a spacious home (measured in square metres) is much more often an advantage enjoyed by high-income households than by low-income households and by people without than with a migration background.

When the residence of a household consists of two or more rooms, it is a reasonable strategy to choose those rooms for sleeping that are least exposed to noise and other environmental bads. Sleeping is a human activity that takes up about one-third of the day and is very important for recreation, subjective well-being, and health. More generally, a household with a spacious home can arrange indoor living routines in a way that minimizes potentially annoying outdoor noise. Noise-exposed rooms are good for purposes that do not involve a lengthy stay, whereas relatively quiet rooms are good for sleeping, relaxing, working, or studying. It can be assumed that the opportunity at home to move to quieter indoor zones makes noise exposure subjectively less annoying and reduces potential stress reactions. In stress research, it is well known that personal control over a situation facilitates coping with stress-prone circumstances (Aldwin, 2007; Biggs, Brough and Drummond, 2017).

A further structural coping strategy aims at building features and construction measures. Independent of dwelling size and indoor arrangements of daily activities, the intrusion of noise and other environmental bads can be reduced by features that improve the construction of a building. Over the last decades, many new and efficient techniques of noise and energy insulation of buildings have been developed and implemented (e.g. McMullan, 2018). With respect to noise, the quality of the windows is particularly important because windows are the weak spots—i.e. the most evident gateway of noise inflow. While there are various industry standards for windows with minimum requirements, modern high-quality soundproofed windows can absorb high noise levels, including potentially annoying aircraft noise. Based on the environmental shielding hypothesis, we expect that the residences of high-income and non-migrant households are more often equipped with better-quality and hence soundproofed windows than low-income and migrant households. The main reason for this expectation is the simple fact that fitting an apartment with high-quality windows requires financial resources.[2]

Data and Methods

The main empirical data for the following analyses come from surveys in two Swiss cities, Bern and Zurich, and two German cities, Hanover and Mainz. We chose these four cities for several reasons. In terms of population and economic and environmental conditions, the four cities are not too different, although there is some variation concerning the institutional and cultural context. Furthermore, environmental issues arising from aircraft traffic was a special topic of our research project, and this motivated the selection of Zurich and Mainz (see below in this section). Moreover, members of our research group were affiliated with the universities in three of the four cites, and this proved helpful both for the survey sampling and for access, guidance, and validation concerning the 'objective' environmental data.

Except for some local adaptations, the surveys in the four cities were strictly comparable in terms of research design (sampling procedure, etc.) and questionnaire program. The surveys were carried out as mail questionnaires and were conducted between October 2016 and March 2017. They were based on random samples of the adult population (18–70 years old) selected from the official population registers managed and maintained by the city administrations. The samples included not only people of Swiss or German nationality but also foreigners and migrants living in the cities.

With some variations in detail, the subjects selected for participation in the study were approached using Dillman's (2007) tailored design method: they received a first invitation to participate in the survey, a postcard after one week, a second invitation after three weeks, and a third invitation after seven weeks. It is important to note that the surveys were not introduced as an environmental survey, but as a survey entitled 'Housing and Living in [City]'. Starting with 4,000 addresses in each city, the survey yielded a response rate of 55.2 per cent in Bern, 48.4 per cent in Zurich, 35.9 per cent in Hanover, and 45.2 per cent in Mainz (standard RR2 for postal surveys to specifically named persons, AAPOR, 2016). In total, 7,540 respondents participated in the survey (for further methodological details of the study, including issues of sample selectivity, see Bruderer Enzler *et al.*, 2019).

Our empirical analyses use several variables from the mail survey. The indicators for the socioeconomic status are household income and migration background. We measure the household's income situation by the net equivalent monthly household income using the new OECD scale (OECD, 2009). To make incomes comparable between Switzerland and Germany, we convert Swiss Francs into Euros and account for the countries' different purchasing power parity (PPP).[3] Migration background denotes whether the respondent, or at least one of his/her parents, was born abroad. Thus, a respondent is assigned a migration status independent of citizenship. We distinguish migration background concerning (a) European and other Western countries (North America, Australia) from (b) Africa, Asia, and South America. Three indicators capture how well a household can shield itself from outside noise: the size of the apartment/house in square meters; a dummy variable indicating whether no bedroom window faces the street versus having at least one window facing the street ('bedroom street-side' for short); and the window quality measured on a scale from 1 to 5. Control variables are the respondent's age, gender, highest educational level (tertiary versus all others), household size, subjective noise sensitivity (index based on five items of the Weinstein (1978) scale; Benfield *et al.* 2014), and a summary index of environmental awareness (with values from 1 to 5, for low to high awareness). People exhibit variation in terms of how sensitive they are towards noise. This in turn might affect their choice of residence. Age, gender, education, household size, and environmental awareness may also have an impact on the decision where to reside. Therefore, we include these variables as 'controls' in the regression equations (for details about the measurement of these variables, see Table A4). We do not, however, want to specify prediction equations by maximizing 'explained' variance. Our main goal is to test the hypotheses elaborated above, and we have tried to avoid 'overcontrolling' of covariates.

In addition, we estimated reduced form equations with (i) income, age, and gender and (ii) migration background, age, and gender to assess the total effects of income and migration background on road traffic and aircraft noise exposure (see Supplementary Tables C1 to C4).

Using the respondents' postal addresses, we were able to determine the spatial coordinates of their places of residence. For the two Swiss cities, spatial coordinates were taken from the Federal Register of Buildings and Dwellings (Swiss Federal Statistical Office, 2017). For Hanover, the software QGIS with the plug-in MMQGIS was used to geocode the addresses based on OpenStreetMap data. For Mainz, the geocoding was carried out using a web-based service that extracts coordinates from Google Maps (www.gpsvisualizer.com/geocoder).

Based on the spatial coordinates, very fine-grained ‘objective’ administrative data on local road traffic and aircraft noise were merged with the survey data (for more information about these administrative data, see Supplementary Section A). Fine-grained data mean that these data focus directly on the building where the respondents live. For both, road traffic and aircraft noise, L_{den} (level during day, evening, night), is used. As a result, noise in dB(A) is assessed as the A-weighted long-term average sound level, applying the usual penalties for evening and night-time noise of 5 and 10 dB, respectively (Brink *et al.*, 2018).

Whereas the road traffic noise data were provided for all four cities, aircraft noise data were only available for Zurich and Mainz. In the regions of Bern and Hanover, there are only small local airports, while Zurich and Mainz are located near international airports. Zurich is affected by Zurich Airport, which is about 10 kilometres north of the city. Mainz is affected by Frankfurt Airport, which is about 25 kilometres east of the city. Zurich Airport has about 750 aircraft movements each day (take-offs and landings), Frankfurt Airport about 1,300. Not all these movements directly affect the cities, and with respect to noise abatement, detailed administrative regulations exist on flight routes, night flights, take-off, and landing procedures – regulations that are more or less continuously in flux. Given this, the development of the airport and, in particular, aircraft noise have been controversial public and political issues in both cities for many years (for Zurich, see e.g. Wirth, 2004; and Bröer and Duyvendak, 2009; for Mainz, see e.g. Schreckenberg *et al.*, 2010; and Wiebusch, 2014).

As we employ geo-referenced individual data, our analytical strategy takes into account that road traffic and aircraft noise pollution levels may be influenced by spatially clustered variables. Concerning the independent variables of the SEM equations, only income is significantly spatially autocorrelated, but there are significant autocorrelations pertaining to the dependent variables of road traffic and aircraft noise, as confirmed by Moran’s *I* tests (see Supplementary Section B). Therefore, we apply SEM with robust standard errors (for a recent summary, see Rüttenauer, 2019b). SEM assumes that the spatial autocorrelation between the units is caused by unobserved factors such as building density, building heights, or neighbourhood topography, and explicitly models the spatial dependence among the error terms. Note that we refrain from autoregressive models because we want to predict the observed values of street and aircraft noise and are not interested in spatial spill-over effects among these variables. For the SEM, we created spatial weight matrices based on inverse distances, with a cut-off distance of 200 m.

Taken together, our study uses detailed individual-level survey data pertaining to sociodemographic and other characteristics of the respondents and their households, as well as to ‘objective’ measures of road traffic and aircraft noise focused directly on the buildings the respondents live in. Compared to previous research, this design avoids problems usually connected with aggregate data of geographical areas, and it circumvents biases accompanying subjective measures of residential environmental conditions. Nevertheless, our data are cross-sectional, and we are well aware that longitudinal data would be preferable.

Empirical Results

Noisy Cities

Table 1 shows descriptive statistics of all variables in the analyses. The socioeconomic composition of the two Swiss and the two German samples is similar concerning age and gender (average age 43–45 years, proportion of females 53–56 per cent), but different with respect to education, income, and the proportion of citizens with a migration background. There are more respondents with a tertiary education in Bern and Zurich than in Hanover and Mainz. The average income (net monthly equivalent household income per capita in Euro, PPP adjusted) in the Swiss cities is about one-third to one-half larger than in the German cities. The proportion of respondents with a migration background is also higher in the Swiss than in the German cities. In all four cities, the migration background is more frequently related to Africa, Asia, or South America (between 15 and 25 per cent of respondents per city).

The World Health Organization (WHO) (2018) strongly recommends not surpassing a road traffic noise level L_{den} of 53 dB. In all cities, the average values are close to the WHO threshold, ranging from 52 dB (Bern) to 55 dB (Hanover). Furthermore, we find remarkably high proportions of residents suffering from potentially detrimental levels of road traffic noise in all cities (Table 1): the share of the respondents enduring road traffic noise above 60 dB is 11.6 per cent in Bern, 19.5 per cent in Zurich, 24.4 per cent in Hanover, and 22.0 per cent in Mainz; the WHO limit of 53 dB is surpassed

Table 1. Descriptive sample characteristics

	Bern	Zurich	Hanover	Mainz
Road traffic noise (dB)	51.93 (6.11)	53.08 (7.11)	55.24 (7.50)	52.87 (8.40)
Share of respondents with road traffic noise greater than 53 dB (%)	36.92	46.77	54.25	38.49
Share of respondents with road traffic noise greater than 60 dB (%)	11.63	19.53	24.41	22.01
Aircraft noise (dB)		45.40 (3.76)		47.65 (3.47)
Share of respondents with aircraft noise greater than 45 dB (%)		51.49		72.51
Share of respondents with aircraft noise greater than 50 dB (%)		11.23		30.14
Net equivalent household income (€)—mean	3,163.85 (1,399.54)	3,400.11 (1,518.27)	2,224.24 (1,247.25)	2,378.08 (1,317.49)
Net equivalent household income (€)—median	2,866.97	3,153.67	2,062.27	2,250.00
Migration background (%)				
None	74.81	58.22	79.18	81.99
West/Europe	9.85	17.20	1.03	1.35
Africa/Asia/South America	15.35	24.58	19.79	16.66
Apartment size (m^2)—mean	92.87 (41.40)	91.65 (42.56)	89.90 (43.02)	91.31 (46.59)
Apartment size (m^2)—median	85.00	85.00	80.00	82.56
Bedroom street side (%)				
No	53.60	50.03	51.11	55.41
Yes	46.40	49.97	48.89	44.59
Quality of windows (1–5)	3.78 (1.09)	3.75 (1.09)	3.56 (1.03)	3.60 (1.05)
Age (years)	43.36 (13.54)	42.92 (13.33)	44.65 (13.93)	42.90 (14.86)
Gender (%)				
Male	44.43	45.77	46.08	46.56
Female	55.57	54.23	53.92	53.44
Education (%)				
Primary/secondary	41.80	41.62	50.04	47.69
Tertiary	58.20	58.38	49.96	52.31
Noise sensitivity (1–5)	3.07 (0.90)	3.12 (0.89)	3.30 (0.85)	3.28 (0.85)
Environmental awareness (1–5)	3.57 (0.82)	3.48 (0.80)	3.51 (0.74)	3.50 (0.72)
Household size (persons)	2.40 (1.23)	2.53 (1.69)	2.35 (1.22)	2.46 (1.21)

Notes: Own calculations of own survey data 2016/2017; arithmetic means, median values and percentage shares; standard deviations in parentheses.

by 36.9 per cent in Bern, 46.8 per cent in Zurich, 54.3 per cent in Hanover, and 38.5 per cent in Mainz.

Turning to aircraft noise, WHO strongly recommends an average L_{den} of no more than 45 dB. As mentioned above, we only have data for Zurich and Mainz. The average level of aircraft noise is higher in Mainz (48 dB) than in Zurich (45 dB). In Mainz, a much higher share of the respondents (30.1 per cent) suffers from very high aircraft noise levels of more than 50 dB compared to Zurich (11.2 per cent). Regarding the WHO recommendation of 45 dB, 51.5 per cent of the respondents in Zurich and 72.5 per cent in Mainz suffer from aircraft noise above this limit.

Residential Environmental Noise by Income and Migration Background

A visual inspection of city maps in Figure 1 gives an impression of districts confronted with high road traffic noise, such as inner-city districts in Zurich or parts of the south of Hanover. However, there is no consistent evidence of a negative relation between income and road traffic noise at the aggregate level of city districts.

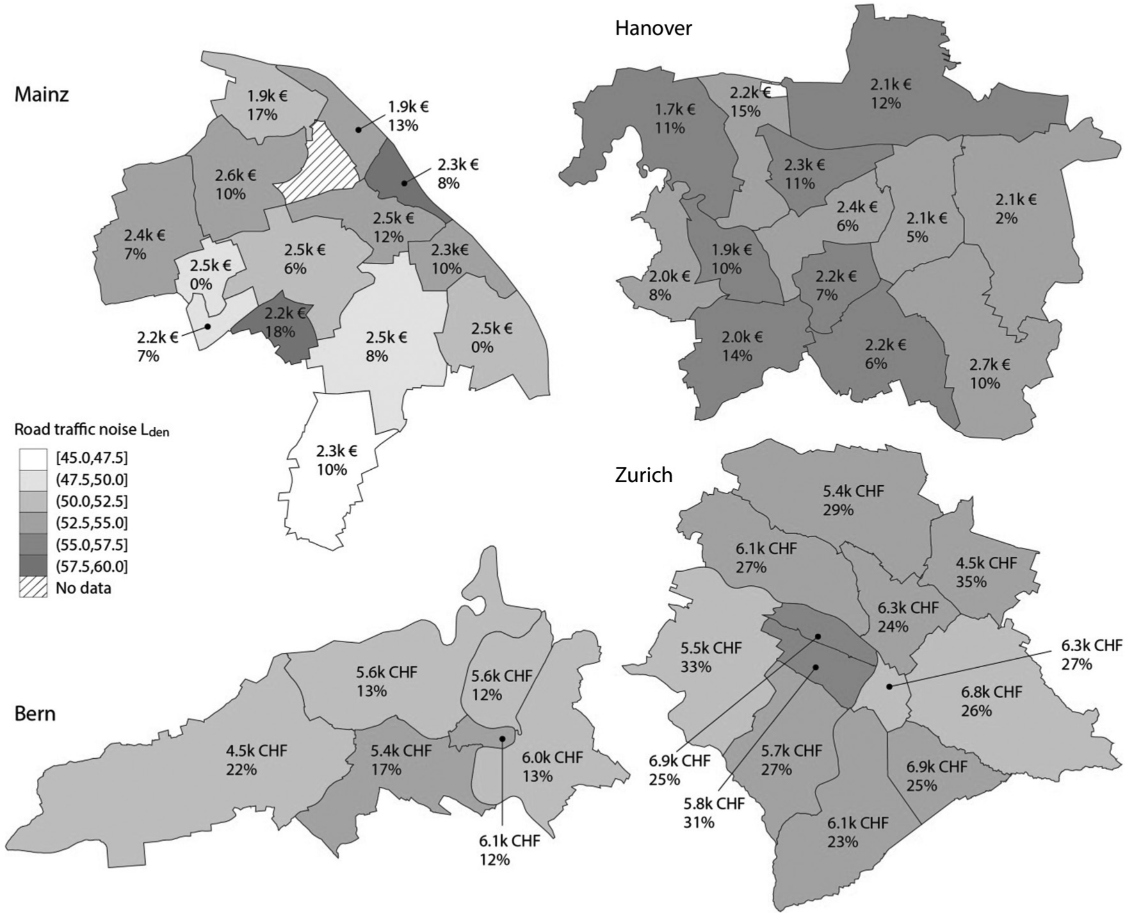

Figure 1. Income, proportion minorities, and road traffic noise level in the districts of the four cities

Notes: Own calculations based on own survey data 2016/2017 and on administrative road traffic noise data.

Notably, in all four cities there are districts that are both noisy and affluent. At the district level, the correlations between average income and average road traffic noise level point in different directions (Bern 0.55, Zurich 0.15, Hanover −0.21, and Mainz −0.22) and none of them is significant. As we will see, working with individual-level data yields different results.

Clearly, individual data are more informative. For each city, we estimated two SEM to analyze the relationship between road traffic noise and the two indicators of social stratification, household income and migration background (see Table A1; for the specification of the estimated equations, see Supplementary Section E). Model 1 includes only these two central independent variables; Model 2 adds control variables—respondent's age, gender, and education, as well as her/his noise sensitivity and environmental awareness. We included the latter two variables as indicators for individual preferences that might influence the location of the residence chosen by the respondents. Figure 2 displays the estimates of Model 2 for each of the cities. Including the control variables, we find a significant negative relation between income and road traffic noise at the respondent's place of residence in the cities of Bern, Zurich, and Mainz. In Hanover, however, the coefficient is close to zero and not significant.

How about the substantial relevance of the coefficients in Bern, Zurich, and Mainz?[4] The coefficient in Mainz, for example, is −0.615 (Model M1 in Table A1); this means that a hypothetical increase in the monthly income by 1,000 € is associated with a reduction of the noise level by about 0.6 dB. Although the magnitude of this effect is not negligible, it is relatively small. A difference of up to 0.7 dB is usually inaudible.

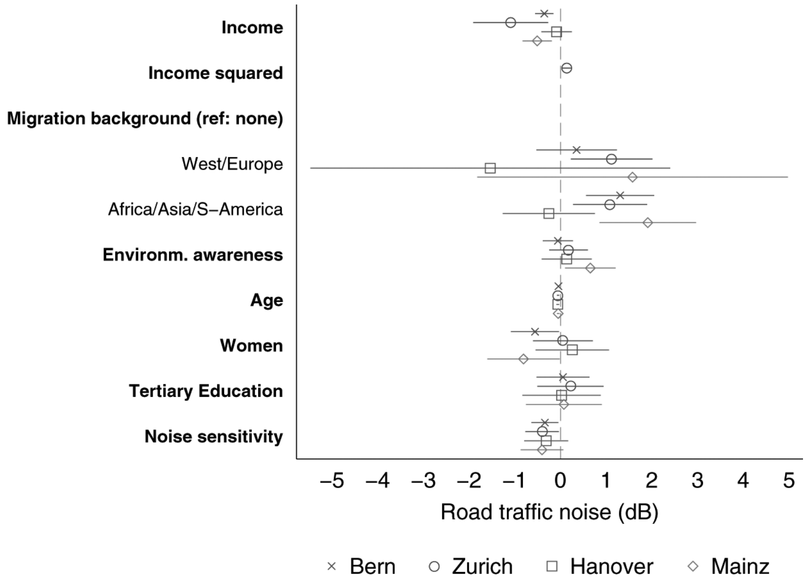

Figure 2. Determinants of road traffic noise

Notes: Based on Table A1, Models B2, Z2, H2, and M2. SEM estimations for income, migration background, and additional covariates; effects are presented with a 95 per cent confidence interval.

It may be helpful to compare the size of the coefficient to the difference in noise levels between cities and the countryside. In the above mentioned study with Swiss data, Diekmann and Meyer (2010) estimated urban–rural differences of 5.37 dB for road traffic noise during the daytime and 4.21 dB during the night-time; the difference is about seven to nine times larger than the income coefficient in the Mainz sample.

Do persons with a migration background face more road traffic noise near their residence? The sign of the coefficients for non-Western migration background is positive and significant in all cities, except for Hanover. In Bern, Zurich, and Mainz, inhabitants with a non-Western migration background live with noise levels that are enhanced by about 1.1–1.8 dB compared to natives. Note that this is an additional burden that adds to low income. In Zurich, Western migrants also experience an increased noise level of similar size to that experienced by residents with a non-Western migration background.[5]

Estimates of income and migration background change only slightly when age, gender, education, noise sensitivity, and environmental awareness are taken into account (models B2, Z2, H2, and M2 in Table A1). Age is negatively associated with road traffic noise at the place of residence. The estimate is similar for all samples. All other things being equal, a resident 10 years older is, on average, exposed to 0.5 dB less road traffic noise than a younger resident. This might reflect a life cycle effect because particularly young respondents (such as students or young employees) live in areas with affordable low rents in noisier neighbourhoods. The noise level of households of female respondents is 0.56 dB lower in Bern and 0.81 dB lower in Mainz than the noise level of households of male respondents. We do not find additional contributions by education. Whereas exposure to road traffic noise tends to show a negative relationship with noise sensitivity, there is no consistent relationship with environmental awareness.

One may argue that the migration coefficients are biased downwards because we have controlled for income. Removing income from the regression equation does not change the overall picture much, although there is a small indirect effect via income. Regression

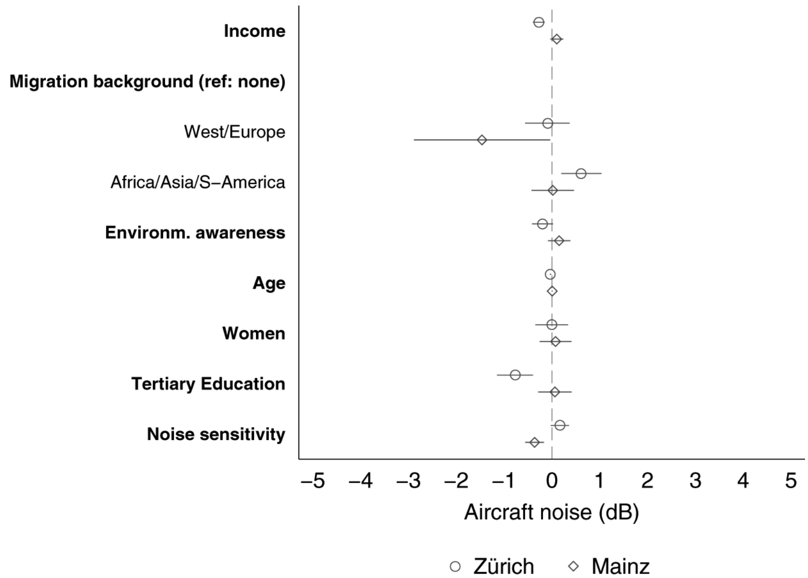

Figure 3. Determinants of aircraft noise

Notes: Based on Table A2, Models Z2 and M2. SEM estimations for income, migration background, and additional covariates; effects are presented with a 95 per cent confidence interval.

coefficients of the reduced form equation for non-Western migration background are 1.639 (0.371), 1.234 (0.393), −0.206 (0.506), and 2.082 (0.536) for Bern, Zurich, Hanover, and Mainz, respectively (standard deviations in parentheses) (see Supplementary Table C2). We also observe only slightly increased income effects when we estimate the reduced form equation without the migration dummies (Table C1). Again, the income coefficients are small but significant in all cities, except Hanover.

As we have argued earlier, aircraft noise constitutes a relevant environmental threat in Mainz and Zurich. However, in Mainz, neither household income nor a non-Western migration background is significantly related to exposure to aircraft noise (Figure 3 and Table A2).[6] In Zurich, the situation is different. According to Model 1 of Table A2, the coefficients for income and migration background are significant, albeit small: a 1,000 € income increase is associated with a 0.337 decrease in aircraft noise level, and having a non-Western migration background enhances the noise level by 0.753. Coefficients are slightly reduced when controlling for age, gender, education, noise sensitivity, and environmental awareness. Excluding income and estimating the reduced form equation (see Supplementary Table C4) leads to a slightly higher estimate of migration background in Zurich. The aircraft noise level for non-Western migrants in Zurich is on average about 1 dB above the level of native citizen due to the indirect effect of migration background via the migration–income correlation.

Shielding against Residential Environmental Noise

In contrast to the rather weak associations between residential environmental noise and income, there is a clear dependency of apartment size on household income in all four cities, even when taking into account several control variables (Figure 4 and Table A3). Income effects are smaller in the Swiss than in the German cities. An additional income of 1,000 € is associated with an increase in apartment size by 9.3 m^2 in Bern and 7.1 m^2 in Zurich and by 10.9 m^2 in Hanover and 11.2 m^2 in Mainz, although part of the difference is due to the higher rent levels in Switzerland. Apartment size is, however, a somewhat indirect indicator of a household's ability to protect itself from external noise. The position of bedrooms in the house and the window quality are more direct indicators. The results for having bedroom windows not facing the street exhibit significant coefficients for Zurich, Hanover, and Mainz (when including control variables), indicating that households with higher incomes are more likely to have bedrooms facing away from the street in these cities (Figure 5 and Table A3). The results for window quality are again in

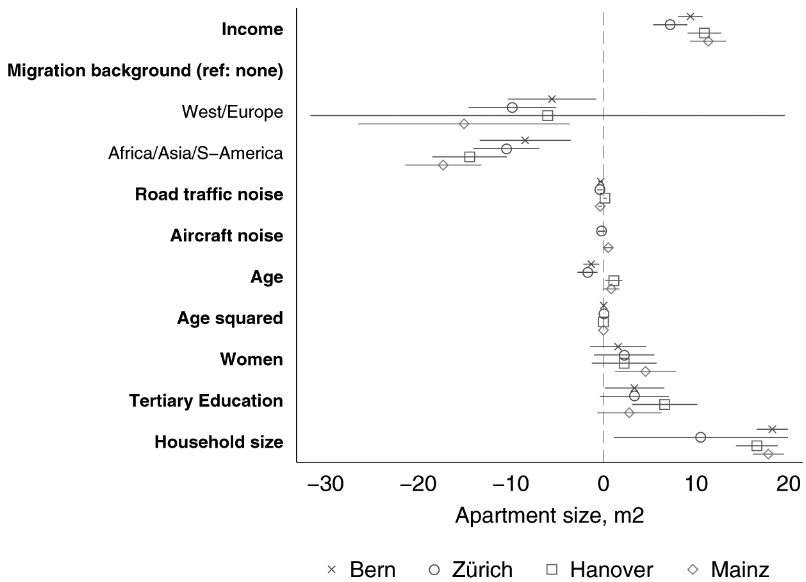

Figure 4. Determinants of apartment size

Notes: Based on Table A3. Linear regression model estimations for income, migration background, and additional covariates; effects are presented with a 95 per cent confidence interval.

line with our expectations. They are most directly related to noise protection, be it road traffic or aircraft noise: with increasing income households have, on average, significantly better window quality in all four cities (Figure 6 and Table A3).[7]

Turning to the associations with migration background, we find a disadvantage in apartment size for respondents with a non-Western migration background for all cities, even though household income (alongside other control variables) is included in the model (Figure 4 and Table A3). Thus, over and above financial reasons, this population group lives in smaller apartments, which we assume to provide a smaller noise protection effect than bigger apartments. However, looking at the more specific indicators for noise protection—bedroom(s) facing away from the street and, in particular, window quality—not all associations are sizable and significant (Figures 5 and 6 and Table A3): for non-Western migrant households, there is a higher probability of having bedroom windows facing the street only in Zurich, while window quality is significantly lower in Bern, Zurich, and Hanover compared to households without a migration background. Thus, there is some evidence that respondents with a non-Western migration background are less able to shield themselves from noise intrusion into their living space, even if their income situation has been taken into account. When income is excluded, the reduced form effects are, as expected, more pronounced. Non-Western households have apartments smaller by about 16, 17, 21, and 25 m^2 in Bern, Zurich, Hanover, and Mainz, respectively, compared to native inhabitants; the probability of having a bedroom that is not on the street side is significantly lower than for native inhabitants in Bern and Zurich; and the window quality is significantly reduced in all four cities (Supplementary Table C6).

To summarize, the relationships (in particular with household income) reveal a clear pattern: high-income households can afford to live in more spacious homes that are more likely to provide options for locating living rooms and bedrooms in the quiet part of the apartment. They also enjoy better window quality than households with a lower level of resources. Thus, our data yield evidence supporting the environmental shielding hypothesis.

Discussion

We have explored the strength of the association between income, migration background, and other sociodemographic characteristics and the environmental burden of road traffic noise in four urban areas in

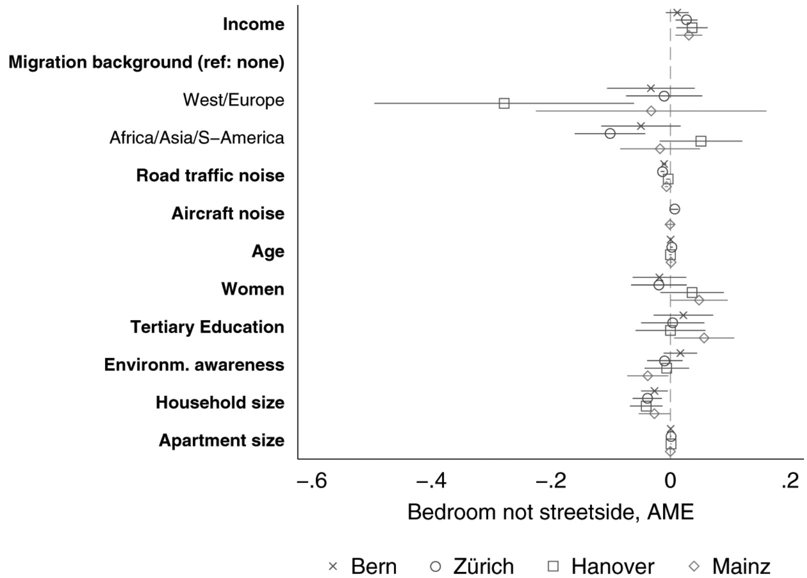

Figure 5. Determinants of having bedroom windows not facing the street

Notes: Based on Table A3. Logistic regression models estimations for income, migration background, and additional covariates; average marginal effects (AME) are presented with a 95 per cent confidence interval.

Switzerland and Germany: Bern, Zurich, Hanover, and Mainz. In addition, we have included aircraft noise in Zurich and Mainz. Four random samples of inhabitants were drawn, resulting in 7,540 completed questionnaires. Households were linked to geo-referenced data of road traffic and aircraft noise. The burden of road traffic noise is high in all four cities: between 12 and 24 per cent of the citizens in Bern, Zurich, Hanover, and Mainz have to endure road traffic noise levels of more than 60 dB and 37–54 per cent endure noise levels above the WHO limit of 53 dB. European Union regulations (directive 2002/49/EC) stipulate that member states should compile noise maps and develop action plans to mitigate noise emissions. However, European communities are far from meeting targets and implementing action plans for noise reduction (Cancik, 2013; European Commission, 2016).

Our first research question focused on the strength of the social gradient of the environmental burden, while controlling for noise sensitivity and environmental awareness as indicators of preferences. As expected, the sign of the income-noise relation was negative in all four cities. The SEM coefficients were small and statistically significant in Bern, Zurich, and Mainz but failed to reach significance in the Hanover sample. Respondents with a non-Western migration background were exposed to more road traffic noise in three of the four cities and the corresponding effects were statistically significant in all except the Hanover sample. Moreover, income and non-Western migration background were also significantly associated with aircraft noise in Zurich, but not in Mainz. Thus, there is evidence for the social gradient hypothesis, but this relationship is not generally valid for all urban areas under study and it is not strong, especially for income. However, there might be cumulative disadvantages for parts of the population, such as young people with low incomes and a non-Western migration background, for whom our regression models predict a greater exposure to high unhealthy noise levels.

Overall, we infer that the impact of the socioeconomic characteristics of income and migration status on the noise level measured outside buildings varies in the cities under investigation. The social gradient is nonexistent in Hanover and the effect is weak to moderate in the other three cities. This is in line with the results of other studies, which have produced only weak evidence or even contradictory findings on the social gradient hypothesis (e.g. Diekmann and Meyer, 2010; Padilla *et al.*, 2014). We believe that local specifics (such as historically grown urban structures; see Elliott and Frickel, 2015) affect how far noise patterns are linked to social disparities (see also Rüttenauer, 2018, 2019a). Interestingly, Rüttenauer's (2019a) study on the emissions of

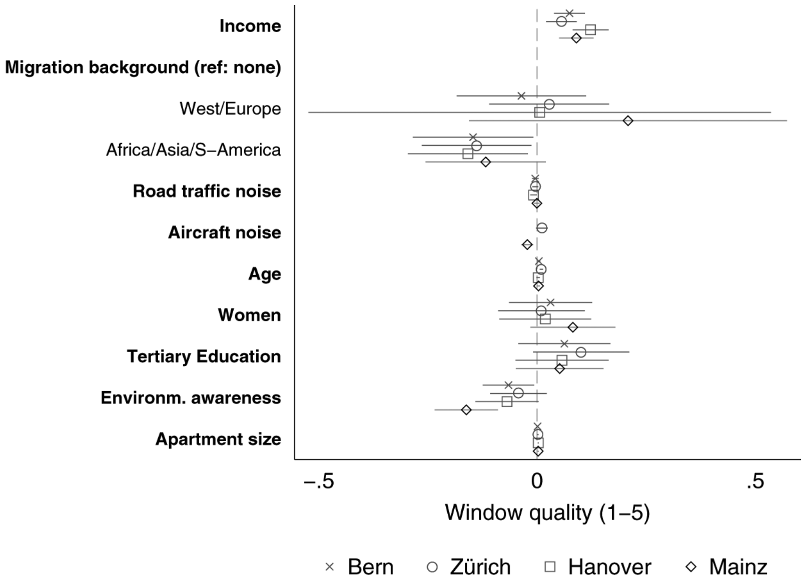

Figure 6. Determinants of window quality

Notes: Based on Table A3. Linear regression model estimations for income, migration background, and additional covariates; effects are presented with a 95 per cent confidence interval.

industrial sites even found a negative association between the share of foreigners and air pollution in Hanover, while the relation was reversed in the city of Mainz. This result is well in accordance with our findings, but the complexity of factors driving the choice of residence also needs to be taken into account. Not only environmental aspects but also rent levels and the attractiveness of inner cities in terms of cultural life, infrastructure (such as public transportation), apartment type and size, and many other characteristics might be considered when choosing where to settle. The relative importance of these factors might also vary over the life course.

In some cities, urban areas and inner cities are attractive, but also noisy. With this in mind, we formulated the environmental shielding hypothesis. When low-income households and those with a higher level of resources alike live in noisy neighbourhoods, we assume that rich people have better capabilities to protect themselves against noise compared to low-income households. The geo-referenced emission data yield valuable information on the noise level outside buildings, but they do not inform us about the noise level inside apartments or about the variation of the noise level in larger apartment buildings. We found evidence for the environmental shielding hypothesis, given the consistent correlation between household income, apartment size, and window quality in all urban areas under study. Thus, households with a higher level of economic resources have a much better chance of reducing noise levels, not just of a busy street in front of their building but also from aircraft if they have good window quality.

In sum, our contribution casts doubt on the hypothesis that there always exists a social gradient of economic resources and social position (indicated by household income and migration background) and the exposure to road traffic and aircraft noise in large cities. At the same time, our results warn against the idea of a ‘democratic’ exposure to environmental bads: economic resources clearly matter when it comes to who is able to shield himself/herself against local noise. Thus, Beck’s (1986: p. 48) well-known statement that ‘poverty is hierarchical, smog is democratic’ needs to be qualified. Individual and household resources shape actual living conditions that are also related to environmental bads.

Although our study contributes to a better understanding of social disparities in terms of exposure to road traffic and aircraft noise in urban areas, it still has a number of limitations that call for further research. First, we consider only four cities in two higher-than-average income countries in Europe, and we focus only on the indicators of road traffic and aircraft noise. Second, our investigation is mainly descriptive; our cross-sectional data do not make it possible to disentangle the specific mechanisms leading to, or compensating for, social disparities in noise exposure. For such an endeavour, we would need longitudinal data that traced moving histories of households and included information on decision processes, combined with fine-grained geographical data. To our knowledge, such data are currently not available for Switzerland and Germany. Third, it would be worthwhile acquiring a deeper understanding of how specific historically grown city types, as well as different strategies in urban transport and road construction policies, relate to social disparities in noise exposure. Fourth and finally, we were only able to scratch the surface of how households with different resources are able to shield themselves from external noise in their homes. It would be an interesting research avenue to collect detailed data on the living conditions and coping strategies of households in noisy urban districts. Further research should dig deeper into the relevance of monetary as well as non-monetary resources and capacities to shield one's household from environmental bads.

Supplementary Data

Supplementary data are available at *ESR* online.

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Notes

1 The 'social gradient' is a standard concept in health science and epidemiology. It denotes a negative correlation between health-risk indicators and socioeconomic status.

2 We are aware that homeownership might be a factor related to the environmental shielding hypothesis. High-income and non-migrant households are more often homeowners, i.e. more likely to live in family-owned houses or apartments, whereas low-income and migrant households tend to belong to the group of house and apartment renters (Andrews and Sánchez, 2011; Garcia and Figueira, 2021). This means homeownership is a mediator of socioeconomic status effects on noise exposure and shielding possibilities such as window quality. In this article, however, we are interested in total status effects.

3 To convert Swiss Francs into Euros, we use the 2016 exchange rate: 1 € = 1.09 CHF (Deutsche Bundesbank, 2021). PPP was established using PPP factors for 2016: Switzerland = 1.202, Germany = 0.753 (World Bank, 2021). Thus, conversion into Euros and PPP is achieved by multiplying incomes in Switzerland by a factor of $(0.753/1.202)/1.09 = 0.57$.

4 We estimated linear and quadratic income coefficients with the samples from all four cities. The quadratic income coefficients were not significant in Bern, Hanover, and Mainz. In the Zurich sample, the linear and quadratic coefficients became significant, while the coefficient was not significant in the linear specification. A negative coefficient of the linear term and a positive coefficient of the quadratic term mean that the strength of the income gradient decreases with increasing income. With the estimates shown in Table A1, Model Z1, the minimum is reached for 4.15 units of the income scale $[0.938/(2 \times 0.113) = 4.15]$ or about 4,150 €. Households above this level have a positive association between income and noise. Note that, except for the apartment size equation in Table A3, the regression equations yield a very low level of explained variance. As stated above, our goal is not to specify equations to maximize 'explained variance'.

5 Large standard errors for Western migration background in the Hanover and Mainz samples are due to the very small proportion of this group in our samples.

6 In Mainz, there is a tendency that respondents with a Western migration background are exposed to a lower aircraft noise level than those without a migration background. The coefficient of 1.46 is significant in Model M2 (Table A2) but fails to reach significance in Model M1 and in Models M1 and M2 of the reduced form estimations (Supplementary Table C4). The lower noise level in comparison to natives might be due to a higher concentration of residents with a Western migration background living in the inner city. This part of the city is less exposed to aircraft noise than the south-eastern periphery of Mainz.

7 The income coefficients are more pronounced when 'migration background' is excluded from the equation (see Supplementary Table C5). However, a causal interpretation of income 'effects' should include the migration variable. Depending on the model specification, migration background is a confounding factor that partially explains the income coefficients.

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Appendix

Table A1. Determinants of road traffic noise (objective), SEM with robust standard errors

	B1	B2	Z1	Z2	H1	H2	M1	M2
Net equivalent household income	−0.352***	−0.353***	−0.938*	−1.088**	−0.180	−0.085	−0.615***	−0.508**
(units of 1,000 €)	(0.096)	(0.102)	(0.413)	(0.417)	(0.158)	(0.170)	(0.152)	(0.162)
Income squared			0.113*	0.133*				
			(0.055)	(0.055)				
Migration background (ref: none)								
West/Europe	0.332	0.353	1.211**	1.119*	−1.575	−1.534	1.402	1.577
	(0.449)	(0.449)	(0.451)	(0.455)	(2.012)	(2.008)	(1.735)	(1.733)
Africa/Asia/South America	1.337***	1.306***	1.089**	1.087**	−0.247	−0.253	1.766**	1.910***
	(0.378)	(0.381)	(0.406)	(0.413)	(0.514)	(0.514)	(0.540)	(0.538)
Age (years)		−0.043***		−0.053***		−0.058***		−0.049***
		(0.010)		(0.012)		(0.015)		(0.014)
Women		−0.556*		0.054		0.260		−0.809*
		(0.268)		(0.334)		(0.409)		(0.404)
Tertiary education		0.055		0.219		0.024		0.075
		(0.295)		(0.369)		(0.436)		(0.423)
Noise sensitivity (1–5)		−0.340*		−0.400*		−0.312		−0.403
		(0.150)		(0.186)		(0.246)		(0.238)
Environmental awareness (1–5)		−0.056		0.177		0.137		0.654*
		(0.169)		(0.215)		(0.279)		(0.282)
Constant	52.778***	56.159***	54.230***	57.226***	55.725***	58.466***	54.109***	55.370***
	(0.344)	(0.899)	(0.749)	(1.294)	(0.442)	(1.392)	(0.441)	(1.368)
Spatial autocorrelation	0.381***	0.375***	0.428***	0.417***	0.575**	0.545*	0.580***	0.579***
	(0.086)	(0.086)	(0.123)	(0.125)	(0.221)	(0.232)	(0.103)	(0.103)
Pseudo R^2	0.014	0.029	0.011	0.025	0.002	0.015	0.018	0.033
N	2,072	2,072	1,843	1,843	1,364	1,364	1,699	1,699

Notes: $^{***}P < 0.001$, $^{**}P < 0.01$, $^{*}P < 0.05$; B, Bern; H, Hanover; M, Mainz; Z, Zurich. Income for Bern and Zurich is converted to Euro and adjusted for purchasing power parity.

Table A2. Determinants of aircraft noise (objective), SEM with robust standard errors

	Z1	Z2	M1	M2
Net equivalent household income (units of 1,000 €)	−0.337***	−0.273***	0.109	0.102
	(0.058)	(0.062)	(0.064)	(0.068)
Migration background (ref: none)				
West/Europe	−0.107	−0.093	−1.222	−1.461*
	(0.236)	(0.237)	(0.724)	(0.726)
Africa/Asia/South America	0.753***	0.618**	0.005	0.019
	(0.211)	(0.215)	(0.226)	(0.226)
Age (years)		−0.027***		0.006
		(0.006)		(0.006)
Women		−0.004		0.077
		(0.174)		(0.169)
Tertiary education		−0.770***		0.063
		(0.192)		(0.177)
Noise sensitivity (1–5)		0.168		−0.361***
		(0.097)		(0.100)
Environmental awareness (1–5)		−0.196		0.152
		(0.112)		(0.119)
Constant	46.364***	47.954***	47.398***	47.721***
	(0.232)	(0.605)	(0.185)	(0.574)
Spatial autocorrelation	0.429***	0.436***	0.557***	0.554***
	(0.126)	(0.125)	(0.104)	(0.104)
Pseudo R^2	0.033	0.052	0.003	0.011
N	1,843	1,843	1,699	1,699

Notes: ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$; M, Mainz; Z, Zurich. Income for Bern and Zurich is converted to Euro and adjusted for purchasing power parity.

Table A3. Determinants of apartment size (linear regression), bedroom street side (logistic regression), window quality (linear regression)

	Apartment size				Bedroom not on street side				Window quality			
	B	Z	H	M	B	Z	H	M	B	Z	H	M
Net equivalent household income	9.261***	7.109***	10.941***	11.202***	0.011	0.028**	0.036**	0.031**	0.082***	0.067***	0.130***	0.094***
(units of 1,000 €)	(0.677)	(0.913)	(0.915)	(0.997)	(0.010)	(0.009)	(0.013)	(0.011)	(0.020)	(0.019)	(0.021)	(0.020)
Migration background (ref: none)												
West/Europe	−5.493*	−10.189***	−5.691	−15.210**	−0.035	−0.007	−0.280*	−0.040	−0.003	0.043	0.025	0.147
	(2.416)	(2.380)	(13.085)	(5.840)	(0.037)	(0.033)	(0.110)	(0.098)	(0.077)	(0.072)	(0.270)	(0.196)
Africa/Asia/South America	−9.333***	−11.977***	−14.463***	−17.510***	−0.047	−0.103***	0.051	−0.017	−0.152*	−0.132*	−0.175*	−0.118
	(2.495)	(1.879)	(2.081)	(2.103)	(0.034)	(0.030)	(0.035)	(0.034)	(0.075)	(0.066)	(0.071)	(0.073)
Road traffic noise (dB)	−0.304*	−0.384*	0.154	−0.348***	−0.011***	−0.013***	−0.004*	−0.007***	−0.005	−0.004	−0.008*	−0.001
	(0.125)	(0.150)	(0.098)	(0.096)	(0.002)	(0.002)	(0.002)	(0.001)	(0.004)	(0.004)	(0.004)	(0.003)
Aircraft noise (dB)		−0.208		0.496		0.007*		−0.001		0.012		−0.025***
		(0.215)		(0.262)		(0.003)		(0.003)		(0.007)		(0.007)
Age (years)	−1.306**	−1.612**	1.160*	0.922*	0.000	0.002*	−0.000	0.001	0.005*	0.010***	0.004	0.004*
	(0.438)	(0.540)	(0.468)	(0.454)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Age squared	0.022***	0.024***	−0.006	−0.002								
	(0.005)	(0.007)	(0.005)	(0.005)								
Women	2.162	2.947	2.384	5.080**	−0.020	−0.018	0.035	0.049*	0.033	0.013	0.033	0.095
	(1.584)	(1.634)	(1.806)	(1.689)	(0.023)	(0.024)	(0.027)	(0.024)	(0.050)	(0.052)	(0.054)	(0.050)
Tertiary education	3.995*	4.095*	6.834***	2.863	0.019	0.006	−0.001	0.057*	0.057	0.106	0.076	0.059
	(1.678)	(1.885)	(1.801)	(1.764)	(0.025)	(0.027)	(0.030)	(0.026)	(0.056)	(0.057)	(0.055)	(0.051)
Noise sensitivity (1–5)	−0.143	−1.772	−1.358	−1.378	0.020	−0.022	0.008	−0.017	−0.109***	−0.142***	−0.090**	−0.135***
	(0.899)	(1.218)	(1.108)	(0.970)	(0.013)	(0.013)	(0.017)	(0.014)	(0.029)	(0.030)	(0.033)	(0.029)
Environmental awareness (1–5)	−2.494*	−2.834*	0.454	−1.691	0.014	−0.006	−0.008	−0.035*	−0.048	−0.024	−0.052	−0.137***
	(1.054)	(1.163)	(1.283)	(1.210)	(0.014)	(0.015)	(0.019)	(0.018)	(0.031)	(0.034)	(0.037)	(0.037)
Household size	18.299***	10.472*	16.539***	17.684***	−0.026*	−0.040**	−0.040**	−0.027*	0.001	−0.017	0.021	0.007
	(0.861)	(4.768)	(1.156)	(0.853)	(0.011)	(0.012)	(0.014)	(0.013)	(0.024)	(0.018)	(0.025)	(0.022)
Apartment size					0.000	0.001	0.001	−0.000	0.001	0.002***	0.002**	0.002***
					(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)
Constant	54.626***	107.608***	−20.066	−10.758					3.916***	3.076***	3.748***	5.062***
	(11.692)	(25.803)	(11.496)	(16.764)					(0.286)	(0.426)	(0.289)	(0.406)
Adj. R^2	0.363	0.256	0.444	0.476					0.034	0.058	0.085	0.084
McFadden Pseudo R^2					0.023	0.061	0.022	0.030				
N	1,956	1,742	1,364	1,699	1,956	1,742	1,364	1,699	1,956	1,742	1,364	1,699

Notes: ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$; robust standard errors in parentheses; B, Bern; H, Hanover; M, Mainz; Z, Zurich. Income for Bern and Zurich is converted to Euro and adjusted for purchasing power parity. For 'Bedroom not on street side' estimates from logistic regressions are presented as average marginal effects (AME).

Table A4. Measurement descriptions

Variables	Measurement/question	Values	Source
Road traffic noise, Bern/Zurich	Noise is modelled at multiple façade points on every floor of a building (Lden)	32–75 dB	sonBASE 2015
Road traffic noise, Mainz	Measured according to the Environmental Noise Directive of the European Union 2002/49/EC (Lden)	32–78 dB	Data from the city environmental office 2012
Road traffic noise, Hanover	Measured according to the Environmental Noise Directive of the European Union 2002/49/EC (Lden)	39–81 dB	Data from the city of Hanover 2015
Aircraft noise, Zurich	Modelled noise levels according to Swiss noise abatement ordinance, day and nighttime (Lden)	33–53 dB	Zurich airport 2016
Aircraft noise, Mainz	Mainz: weighted long-term average sound levels for day and nighttime (Lden)	38–51 dB	Gemeinnützige Umwelthaus GmbH 2016
Age (years)	In which year are you born?	18–72 years	Own questionnaire
Gender	Are you. . .?	Male, female	Own questionnaire
Education	Bern/Zurich: Please state your highest educational degree?	Primary/secondary, tertiary	Own questionnaire
	Hanover/Mainz: What is your highest general educational degree? What is your highest vocational degree?	Primary/secondary, tertiary	
Net equivalent household income (Bern/Zurich, CHF)	Please state your personal monthly net income and that of your household. The net income includes all incomes (child allowances, rents, pensions, etc.) minus AHV/IV and pension fund contributions. And what is the monthly net household income of all household members combined?	353–15,000 CHF	Own questionnaire
	How many persons live in your household (including you)? And how many of them are children . . . at the age of 0–6 years? . . . at the age of 7–13 years?		
Net equivalent household income (Hanover/Mainz, €)	Please state your personal monthly net income and that of your household. The net income includes all incomes (child allowances, rents, pensions, etc.) minus contributions to social security insurances. And what is the monthly net	302–10,000 €	Own questionnaire

(continued)

Table A4. (Continued)

Variables	Measurement/question	Values	Source
	household income of all household members combined? How many persons live in your household (including you)? And how many of them are children . . . at the age of 0–6 years? . . . at the age of 7–13 years?		
Migration background	In which country are you born? In which countries are your father and mother born in?	a) No migration background, b) West/Europe, c) Africa/ Asia (incl. Turkey)/South America Migration background denotes whether respondent or at least one of his/her parents is born abroad.	Own questionnaire
Noise sensitivity	1) I get annoyed when my neighbours are noisy. 2) I get used to most noises without much difficulty. 3) I find it hard to relax in a place that's noisy. 4) I get mad at people who make noise that keeps me from falling asleep or getting work done. 5) I am sensitive to noise. Adapted from the Weinstein (1978) scale, see also Benfield et al. (2014).	Mean index from 1 = not sensitive to 5 = sensitive, coding for item (2) was reversed, additive index	Own questionnaire
Environmental awareness	Please indicate how much you agree to the following statements. 1) The thought of the environmental conditions under which our children and grandchildren will probably have to live worries me. 2) If we continue as we are, we are heading for an environmental catastrophe. 3) The majority of the population in our country is too little environmentally conscious. 4) Environmental problems are greatly exaggerated by many environmentalists. 5) Politicians in our country do far too little for environmental protection. 6) For the sake of the environment, we should all be prepared to limit our standard of	1 = do not agree at all to 5 = fully agree, additive index	Own questionnaire

(continued)

Table A4. (Continued)

Variables	Measurement/question	Values	Source
	living. Modified version of the Diekmann and Preisendörfer (2003) scale.		
Quality of windows	How would you rate the overall quality of the windows in your living spaces?	1 = very bad to 5 = very good	Own questionnaire
Bedroom street side	Does at least one window of your bedroom face the street?	Yes, no	Own questionnaire
Apartment size (m^2)	How big is the living area of your apartment? (without cellar and without attic)	8–500 m^2	Own questionnaire
Household size	How many persons live in your household altogether?	1–11	Own questionnaire

Notes: Values are taken from the sample used for the analyses.