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Selected aspects of the urban environment in relation to human health

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An analysis of residential road traffic noise and surrounding greenness in the Heinz Nixdorf Recall study

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1 Introduction

"Have you ever thought about how the way we design and build our communities can affect our health?" (Howard Frumkin)

1.1 Urban health

Due to today's globally increasing urbanization and population growth, a majority of the world's population is living in urban areas. In 2014, the share was estimated to 54% and is projected to further grow during the coming decades, reaching 66% in 2050 (United Nations Department of Economic and Social Affairs, Population Division 2015).

The links between urban planning and public health are numerous and complex. It is therefore important to gain a deeper understanding of how urban environments affect health and can produce health benefits. This has also been recognized by the World Health Organization (WHO), taking form in the Healthy Cities project, a global movement (Duhl and Sanchez 1999; Hancock 1993).

Living in an urban area can have many advantages. Ideally, it offers an infrastructure with well-built roads and housing and a public transportation system. City life comes with a range of cultural and social events and offers the chance to connect with a variety of different people. It further increases the chances of professional development through a suitable occupation and education at a school or college; students in urban schools have been found to perform better than their rural counterparts, irrespective of socioeconomic background (Organisation for Economic Co-operation and Development (OECD) 2010).

On the negative side, city life implies exposure to crowding, crime, air pollution and noise (WHO Regional Office for Europe 2010b). Big cities are commonly densely built, with sealed surfaces, high rise buildings and traffic lanes dominating the environment. Green and calm open spaces are often rare, and urban heat island effects are a health risk resulting from the density of cities (McGeehin and Mirabelli 2001; Tan et al. 2010).

In terms of health, a so-called 'urban advantage' has been described, implying that on average, urban populations are at an advantage compared with rural populations considering health outcomes (Rydin et al. 2012). However, this does not always apply. Especially in low-income populations (and in developing countries) the opposite can be the case, with urban populations experiencing worse health compared with their rural counterparts ("urban penalty"), while their richer urban neighbors still can benefit from an urban advantage (Sverdlik 2011). Taken together, urban populations in high-income countries on average fare better than those in low-income countries and better than rural populations, but intra-country and intra-urban inequality persists. Therefore, an increase in urbanization taken alone will not improve global health, but an urban advantage in health needs to be actively promoted through policy and planning, especially in the poorest urban populations in every country (Rydin et al. 2012).

This thesis is based on data from the German Heinz Nixdorf Recall (HNR) study, which is conducted in the cities Mülheim/Ruhr, Essen and Bochum within the highly urbanized Ruhr area. It hence refers to an urban population in a high-income country, but also represents an area with great intra-urban socioeconomic variety.

1.2 Environmental noise and health

A main issue of urban environments is noise. Noise is defined as a sound which is loud, unpleasant or causes disturbance (Oxford Dictionary 2017). Early research on health effects of noise has mainly focused on occupational noise exposure, which was found to cause ear damage and even hearing loss (Stucken and Hong 2014). This knowledge has resulted in various regulations concerning noise exposure limits and protection measures at the work place. In Germany for example, first regulations on occupational noise were issued in the mid-1970s; amongst the most important today is the *Lärm- und Vibrations-Arbeitsschutzverordnung* (LärmVibrationsArbSchV 2007). During the past decades, the relevance of environmental noise exposure as a stressor and health risk has also been increasingly recognized. Environmental noise could be considered a less 'acute' problem then occupational noise in the sense that it is rarely loud enough to damage ear drums. However, particularly chronic exposure to environmental noise can affect health in many ways (Babisch 2005; Stansfeld et al. 2000a). Further, environmental noise affects large parts of the population. In the European countries, 125 million people were estimated to be exposed to road traffic noise levels >55 dB in 2012 (European Environment Agency 2014).

Road traffic represents a main source of environmental noise in urban areas (WHO Regional Office for Europe 2011). Exposure to road traffic noise causes stress and annoyance and interferes with activities of daily living, e.g. communication and concentration on tasks (Babisch 2005, 2003). Research has revealed associations of traffic noise exposure with non-auditory health outcomes. For example, it has been linked to increased blood pressure and hypertension (Fuks et al. 2011; Barregard et al. 2009; Chang et al. 2013), myocardial infarction (Babisch et al. 2005; Selander et al. 2009), stroke (Sørensen et al. 2011), and diabetes (Sørensen et al. 2012). Cardiovascular health effects of traffic noise are well researched (Münzel et al. 2014) and have also been found in analyses of the HNR study (Fuks et al. 2011; Kälsch et al. 2014).

Evidence is accumulating for an association of environmental noise with mental health outcomes as well (van Kamp and Davies 2008; Stansfeld et al. 2000b), but to date only few prospective studies have been published. Traffic noise exposure may impair mental health via mechanisms like stress (Rylander 2004) or via sleep disturbance conditions such as insomnia (Halonen et al. 2012), which have shown associations with depression in previous studies (Franzen and Buysse 2008; Riemann and Voderholzer 2003; Roberts et al. 2000). Reducing the burden of mental health disorders is an important public health aim according to the WHO (World Health Organization (WHO) 2013), which makes mental health an important topic to study in the context of environmental exposures.

The necessity of basing urban planning processes on public health requirements has been broadly recognized (Duhl and Sanchez 1999). Further studies are needed to strengthen the evidence for traffic noise effects on mental health in order to provide urban planners with the knowledge they need to create healthy urban environments. Therefore, one aim of this thesis was to investigate the effect of long-term residential exposure to road traffic noise and depressive symptoms, using data from the HNR study.

1.3 Greenness and health

Greenness is another environmental feature which is increasingly studied in connection to health (Hartig et al. 2014). Green and natural environments are intuitively perceived pleasant and soothing. City dwellers seek recreation from stress and hectic everyday life in nature; they go hiking, take a walk in the woods or relax in a park with family and friends.

In contrast to traffic noise exposure, green environments have been linked to better population health and reduced mortality in previous research (Gascon et al. 2016; Gascon et al. 2015; Maas 2006; Lee and Maheswaran 2011; WHO Regional Office for Europe 2016). Studies have for example found beneficial associations of green environments related to birth outcomes (Dadvand et al. 2012; Hystad et al. 2014), blood pressure (Markevych et al. 2014) and diabetes (Astell-Burt et al. 2013).

Several pathways to explain how greenness can influence health have been suggested. For example, green vegetation like trees can improve the air quality in urban areas (Pugh et al. 2012). Green spaces may also foster health by encouraging physical activity or promoting social interaction (Dadvand et al. 2016; de Vries et al. 2013; Maas et al. 2009; Maas et al. 2008; Maas et al. 2009). An early hospital study (Ulrich 1984) investigated differences in postoperative recovery in two matched groups of patients viewing either green trees or a brick wall from their hospital window. In comparison, the patients with the tree view had shorter postoperative hospital stays and took fewer moderate and strong analgesic medication doses (Ulrich 1984). More recent studies similarly suggest that viewing green and natural environments (e.g. from the window) can already have a positive impact on health by alleviating stress and facilitating mental restoration (Ulrich et al. 1991; Kaplan 2001; Honold et al. 2016). A study that used functional magnetic resonance imaging to evaluate brain activation areas in response to viewing rural (green) and urban living environments found that during rural scene viewing the predominantly active brain regions were amongst those related to positive and pleasant emotions, e.g. the putamen (Kim et al. 2010). For the urban pictures the regions activated by negative emotions, e.g. the amygdala, showed dominant activity. Also, the rural pictures were subjectively considered more 'peaceful' by the participants (Kim et al. 2010), which supports the mental restoration theory.

Based on these findings the hypothesis is that green environments may promote health and well-being. This would also be in line with the so called 'biophilia hypothesis' introduced by Edward O. Wilson (Wilson 1984). It describes an innate affinity towards nature and other living beings which is deeply rooted in the human biology as a result of evolution. Thus, humans would be born with a preference for natural elements and surroundings and consequently, a lack of these may impair their well-being.

Different methods to measure greenness exist. Health studies apply different subjective (e.g. perceived greenness, reported outdoor activity) or objective measures of green (Jorgensen and Gobster 2010). Objective exposure to green space is commonly measured either as *surrounding greenness* or *access to green space* (e.g. distance to nearest park), which are two different concepts. Surrounding greenness is typically measured within a certain area (often buffer around a residence) using either the percent green space derived from land-cover data or the Normalized Difference Vegetation Index (NDVI) derived from satellite imagery. Use of comparable standardized measures of greenness, like the NDVI, has been recommended for future studies (Gascon et al. 2015). Therefore, an aim of this thesis was to study the association of residential surrounding greenness measured by NDVI with general health in the HNR study.

1.4 Socioeconomic position, the neighborhood and social relations

Socioeconomic position (SEP) is a commonly applied concept in health research and refers to the social and economic factors that influence the positions of individuals or groups within a society. These include for example education, income and employment status (Galobardes et al. 2006). Environmental resources (e.g. availability of greenness, clean air) and risks are often unequally distributed across different SEP groups. For example, individuals with a lower SEP, or residing in neighborhoods with lower SEP (defined e.g. by higher unemployment rates), tend to have less access to green space and to be exposed to higher levels of traffic noise. This pattern has been observed in various studies in Germany as well as in other countries (Bocquier et al. 2013; Braubach and Fairburn 2010; Havard et al. 2011; Hoffmann et al. 2003; Laußmann et al. 2013; Kohlhuber et al. 2006). It is a well-established fact that SEP represents a major determinant of health and health inequalities (Marmot 2005). Numerous studies have shown that a lower SEP is associated with worse health and increased mortality (Mackenbach et al. 2008; Major et al. 2010). When it comes to the distribution of urban health risks and resources, obvious inter- and intra-urban differences exist. This may further add to the observed health disparities

(Evans and Kantrowitz 2002; WHO Regional Office for Europe 2010a). One of the WHO European Healthy Cities Network's overarching goals is therefore to improve health for all and to reduce health inequalities through involvement of the local governments (WHO Regional Office for Europe 2013).

Both physical and social aspects of the neighborhood environment and how they are perceived can influence residents' health (Poortinga et al. 2007). Social relationships and networks are important health resources (Chuang et al. 2013; Umberson and Montez 2010) and represent a core aspect of the so called 'social capital' (Coleman 1988). Studies have found that living in deprived neighborhoods is associated with lower social capital (Nettle et al. 2011; Hill et al. 2014). Further, physical attributes of neighborhoods may contribute to the health effects of social aspects (Macintyre et al. 2002). Hence, it is important to remember that the socio-economic context cannot be neglected when studying the health impacts of environmental exposures like noise and green space.

To create residential environments that promote health and wellbeing of the residents and provide high levels of satisfaction is challenging (Braubach 2007). So far, the relationships between residential greenness, social relations, neighborhood social capital and neighborhood satisfaction have rarely been studied, particularly in combination with health. Hence, this was a further aim of the present thesis.

2 Aim and objectives

This thesis is based on the well-founded hypothesis that certain aspects of the urban environment promote human health while others represent a risk. The overall aim was to investigate health in relation to 1) road traffic noise as a potential risk factor and 2) greenness as a potentially health-promoting attribute of the built environment.

To gain deeper insight into the relationships between the physical and social environment and health, the specific objectives of this thesis were to analyze

1) the impact of residential road traffic noise on depressive symptoms in a longitudinal study design,
2) the association of residential surrounding greenness (NDVI) with self-rated health, and
3) the interrelationships of residential surrounding greenness (NDVI) and self-rated health with subjectively perceived aspects of neighborhood environment (*neighborhood satisfaction*, *perceived safety*) and social relations (*social satisfaction*, *neighborhood social capital*), using a cross-sectional study design.

The thesis comprises two manuscripts that have been published in the international peer-reviewed journals *Environmental Health Perspectives* (addressing objective 1) (Orban et al. 2016) and *Journal of Urban Health* (addressing objective 2 and 3) (Orban et al. 2017). Both manuscripts can be found in the Appendix.

I developed the research questions and study design, performed the statistical analyses and interpreted and discussed the results for both publications. Comments and suggestions from my supervisor and co-authors as well as from the reviewers were taken into consideration.

3 Methods

3.1 Study population

The two publications included in this thesis are based on data from the Heinz Nixdorf Recall (HNR) study. This ongoing cohort study is conducted in three adjacent cities (Bochum, Essen and Mülheim/Ruhr) in the Ruhr metropolitan region in Germany (Figure 1). The HNR study area covers a region of approximately 600 km^2 (Hennig et al. 2014). Between 2000 and 2003 (baseline), 4,814 men and women aged 45-75 years from a random population registry sample were enrolled (Schmermund et al. 2002). The examinations were performed in the Heinz Nixdorf Study Center in Essen and included e.g. standardized anthropogenic measurements, interviews and blood sampling. The baseline response calculated as recruitment efficacy proportion was 55.8% (Stang et al. 2005). Two follow-up examinations took place five and ten years after the baseline examination. The study maintained extensive quality management procedures, including a certification and re-certifications according to DIN ISO 9001:2000/2008. All participants provided written informed consent and the study was approved by the institutional ethics committee (Erbel et al. 2010).

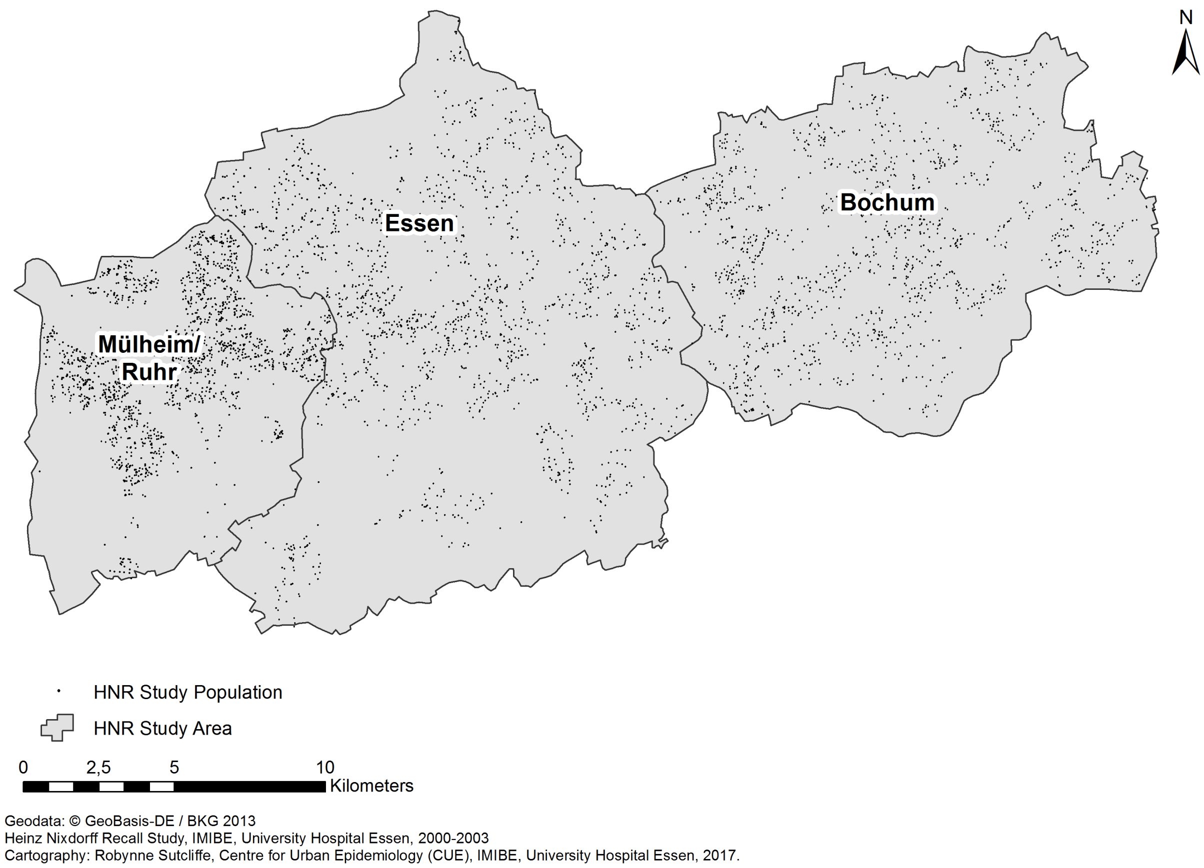


Figure 1 Map of the Heinz Nixdorf Recall study area and the distribution of participants' residences in the cities Mülheim/Ruhr, Essen and Bochum.

3.2 Data collection and variable definitions

3.2.1 Exposure assessment

Road traffic noise

Road traffic noise (Orban et al. 2016) was assessed within the scope of the cities' *Lärmkartierung* according to Directive 2002/49/EC of the European Parliament and Council of the European Union (European Parliament, Council of the European Union 2002). It was modelled for the year 2006 as weighted average day–evening–night (L_{den}, 24-hour) and nighttime (L_{night}, 22:00–06:00 h) sound levels in 5–dB(A) categories (Figure 2). Small-scale topography of the area, dimensions of buildings, noise barriers, street axis, vehicle type-specific traffic density, speed limit, and type of road surface were considered in the modelling process. These data were linked to the geographic residences of the study participants at baseline (2000-2003) using a geographic information system (ArcGIS) and assuming average noise levels to be relatively stable over the five-year follow-up period. High noise exposure was defined as L_{den} >55 dB(A), based on the maximum community noise levels recommended by the WHO (Berglund et al. 1999).

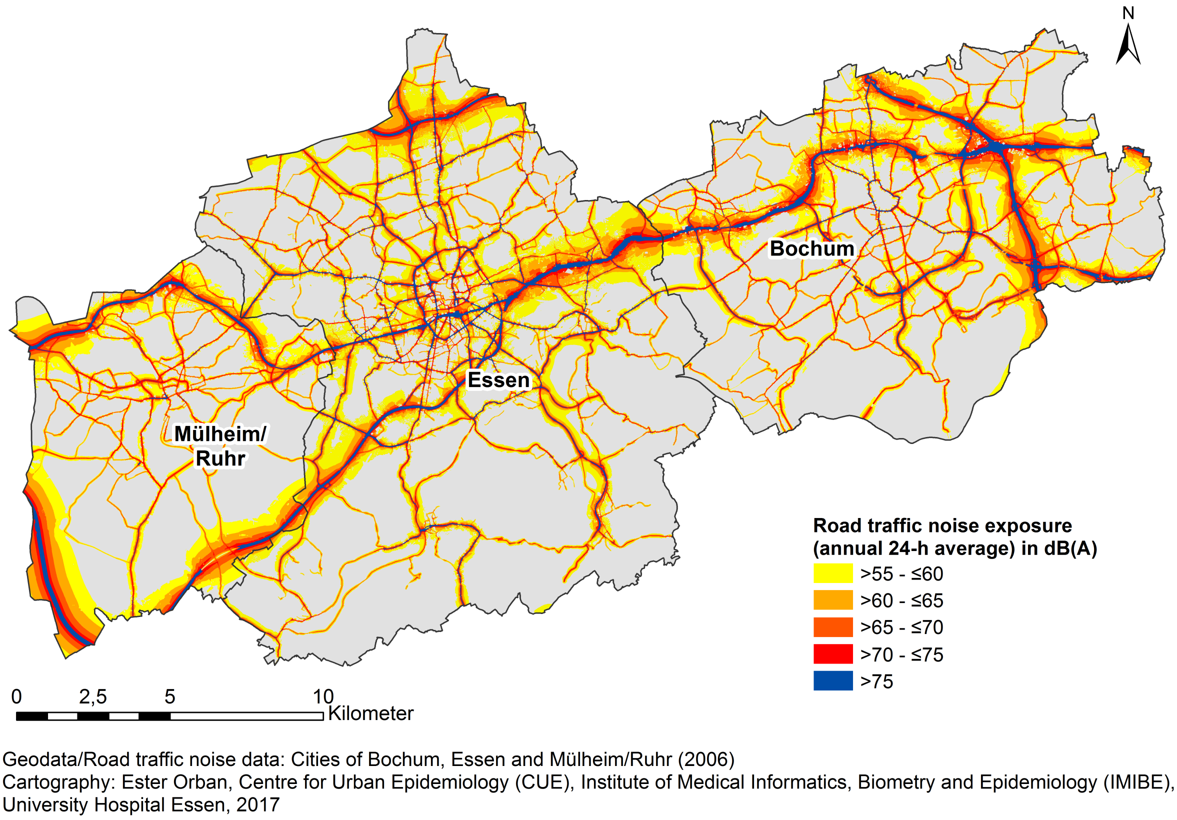


Figure 2 Distribution of road traffic noise in the Heinz Nixdorf Recall study area. Grey areas indicate traffic noise levels (L_{den}) ≤55 db(A).

Residential surrounding greenness

Level of surrounding greenness (Orban et al. 2017) at each participant's residence was measured using the Normalized Difference Vegetation Index (NDVI) (Rhew et al. 2011). The NDVI originally found application as an indicator of drought and is commonly applied to measure the presence and level of green vegetation and to monitor fluctuations over time, using remote sensing data (Weier and Herring 2000). The principle underlying the NDVI is that healthy green vegetation absorbs most of the visible (red) light (VIS) that reaches it for use in photosynthesis, and reflects a large proportion of the near-infrared light (NIR). In comparison, unhealthy or sparse vegetation reflects more VIS and less NIR.

Based on these differences in reflectance, the formula

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)}$$

is used for calculating the NDVI (Weier and Herring 2000; Rhew et al. 2011).

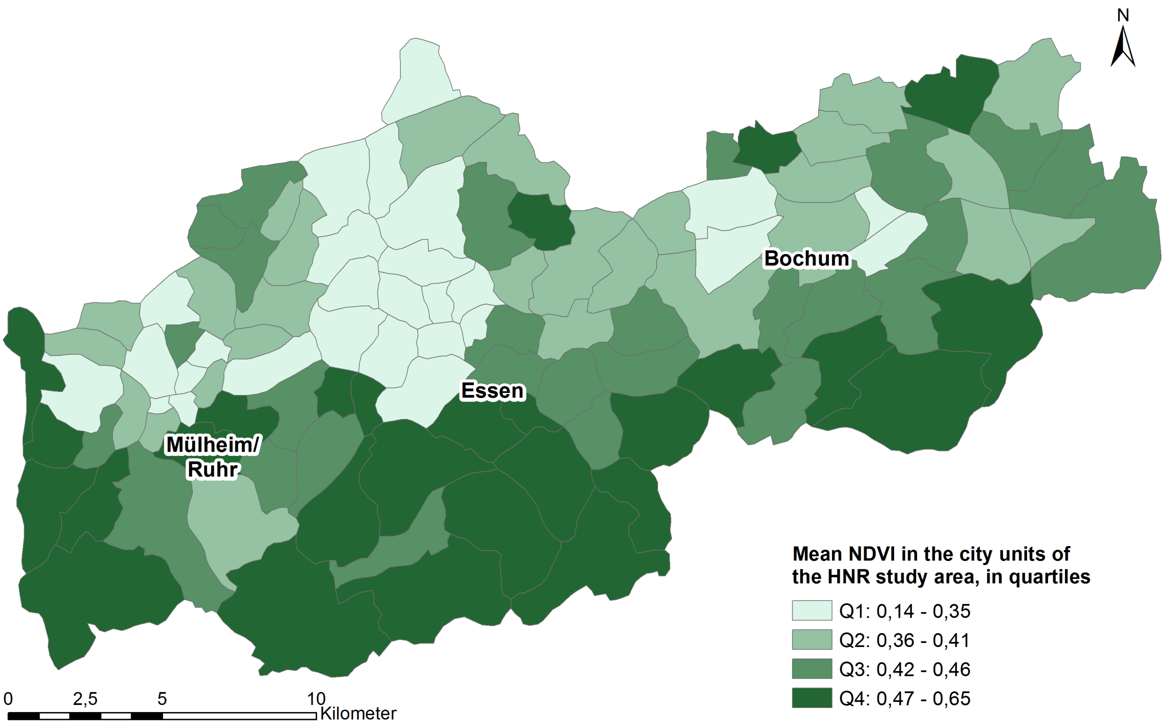
Values of the NDVI can range from −1 to +1; those approaching −1 generally correspond to water, while values around 0 represent bare surfaces with no vegetation, e.g. rocks, rooftops or roads, and a value of 1 represents the densest possible green vegetation (Weier and Herring 2000).

NDVI across the HNR study area was calculated based on United States Geological Survey (USGS) Landsat 5 Thematic Mapper satellite data (captured 10 July 2003, a cloudless day) with a 30-m resolution which was available from the Landsat Archive (United States Geological Survey). Spectral bands 3 (visible red, wavelengths 0.63-0.69μm) and 4 (near-infrared, wavelengths 0.76-0.90 μm) were used to calculate the NDVI with the geographic information system (GIS) ArcMap 10.3.1 by means of the above-mentioned formula. After excluding negative NDVI values to eliminate any confusion of water – a potentially beneficial environmental exposure – with absence of greenness, we calculated the mean NDVI within a buffer of 100m around the participants' baseline addresses (Figure 3) using Geospatial Modelling Environment. To apply a broader scale of neighborhood, we also calculated the NDVI in a 1000-m buffer.

Figure 4 shows the mean NDVI on city unit level in the HNR study area. An obvious north-south gradient is visible, with the southern parts showing higher levels of greenness.

Geodata Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community; Normalized Difference Vegetation Index (NDVI) Data: calculated from USGS Landsat 5 Thematic Mapper data (10 July 2003), http://earthexplorer.usgs.gov ; Cartography: Ester Orban, Centre for Urban Epidemiology (CUE), IMIBE, University Hospital Essen, March 2017

Figure 3 Normalized Difference Vegetation Index (NDVI) in a 100-m buffer. Left: Aerial image of a residential area. Right: Raster layer with NDVI grid cells (30x30m) on the same area. This example shows a mean NDVI of 0.42 in the 100-m buffer.



Geodata: Cities of Bochum, Essen and Mülheim/Ruhr (2014)
NDVI: Calculated from USGS Landsat 5 Thematic Mapper data (10 July 2003) http://earthexplorer.usgs.gov
Cartography: Ester Orban, Centre for Urban Epidemiology (CUE), Institute of Medical Informatics, Biometry and Epidemiology (IMIBE), University Hospital Essen, 2017

Figure 4 Map of mean NDVI (10 July 2003) in the city units of the Heinz Nixdorf Recall study area, depicted in quartile categories.

3.2.2 Health outcomes

Depressive symptoms

In the HNR, depressive symptoms during the previous seven days were assessed using the validated German 15-item version of the Center for Epidemiologic Studies Depression scale (CES-D) (Radloff 1977; Hautzinger et al. 2012). Self-administered questionnaires were handed out at baseline and at the five-year follow-up examination visit. The CES-D is a screening tool developed to measure current depressive symptoms in the general population. It has been validated in different populations and settings and is frequently applied in health research (Radloff 1977; Hautzinger et al. 2012). The applied scale consists of 15 statements, e.g. 'During the last 7 days I felt sad', '... I felt lonely', '...I felt that everything I did was an effort', '... I had difficulties concentrating' or '...I felt that I could not shake off the blues even with help from my family or friends'. Each statement is answered by indicating how often the person felt that way (during the past 7 days): '0=Rarely or none of the time (less than 1 day)', 1='Some or a little of the time (1-2 days)', 2='Occasionally or a moderate amount of time (3-4 days)' or 3='Most or all of the time (5-7days)'. Two of the 15 statements are positive (e.g. '.... I felt happy'), and their responses are thus reversely coded. The CES-D score is calculated from the sum of these responses and ranges from 0 to 45, with higher levels indicating more and/or more frequent depressive symptoms. For up to 3 missing answers, the mean of the remaining item responses was imputed; for questionnaires with more than 3 missing responses, the score was not calculated.

Antidepressant medication intake was additionally included in the definition of depressive symptoms, because it is indicative of clinically relevant depression. Furthermore, it may lower CES-D scores in treated depressive individuals. Participants were asked to bring along all medication including packages ('brown bag' method) taken in the last seven days to the examination visits. Intake of antidepressant medication was defined as Anatomical Therapeutic Chemical (ATC) groups N06A or N06CA.

Study participants with a CES-D score ≥17 and/or taking antidepressant medication were defined as cases of high depressive symptoms. This definition was applied both at baseline and at the five-year follow-up.

Self-rated health

Self-rated health is an extensively used measure of general health status in public health and survey research. It is easily administered, mostly through a single item (Bombak 2013).

For the analyses in this thesis (Orban et al. 2017) we used information on self-rated health collected at the baseline examination of the HNR study. Self-rated health was assessed in a standardized computer-assisted personal interview (CAPI) by the question 'How would you describe your overall health status during the last twelve months?' on a five-point Likert scale ('very good', 'good', 'fair', 'poor' or 'very poor'). Poor self-rated health status was attributed to participants answering 'poor' or 'very poor'.

While self-rated health represents a subjective measure allowing respondents to prioritize and evaluate different aspects of their health, it has shown high consistency with objectively measured health status (Wu et al. 2013). Moreover, it has been suggested to be a useful tool for epidemiological research also in low-income settings (Subramanian et al. 2010).

3.2.3 Neighborhood environment and social relations

Different variables addressing aspects of neighborhood environment and social relations were analyzed, namely: *neighborhood satisfaction*, *perceived safety*, *social satisfaction* and *neighborhood social capital*. These variables were considered both as exposures (in relation to self-rated health) and as outcomes (in relation to residential surrounding greenness), as depicted in Figure 5.

To date, no consensus exists in urban health research regarding the definition of 'neighborhood' and its boundaries, and several different approaches have been used (Weiss et al. 2007). For the present study, participants rated satisfaction with their neighborhood and social relations, as well as trust in neighbors, helpfulness of neighbors and perceived neighborhood safety in a questionnaire handed out at the baseline examination. It is important to notice that the term 'neighborhood' was not further defined in the questionnaire. Thus, it represents a matter of subjective interpretation which may vary between different participants.

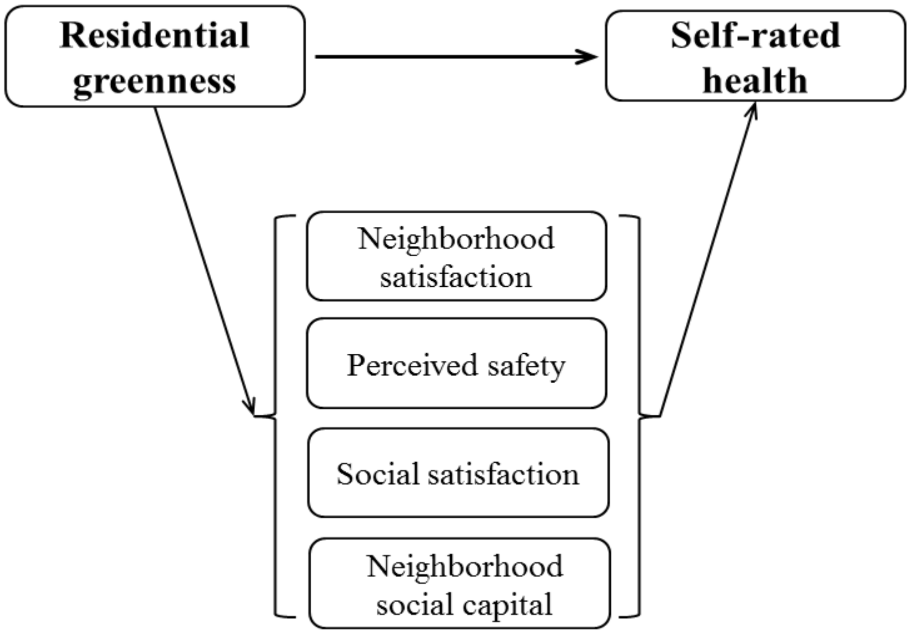


Figure 5 Overview on the analyzed associations between residential surrounding greenness, self-rated health and neighborhood environment and social variables in this thesis (Orban et al. 2017).

In the questionnaire, the questions 'How satisfied are you with your residential area (in German: 'Wohngegend')?' (*neighborhood satisfaction*) and 'How satisfied are you with your relations to friends, neighbors, acquaintances?' (*social satisfaction*) could be answered by 'very unsatisfied', 'rather unsatisfied', 'rather satisfied' or 'very satisfied'. Both items were dichotomized with 'very/rather unsatisfied' being the negative and 'very/rather satisfied' the positive response.

Agreement with the statements 'Most people in my neighborhood are helpful', 'I can trust most people in my neighborhood' and 'I feel safe during daytime in the area where I live' (*perceived safety*) was expressed by the options 'fully disagree', 'rather disagree', 'rather agree' or 'fully agree'. These items were dichotomized, with 'fully/rather disagree' being the negative and 'fully/rather agree' the positive response. The information on trust in and helpfulness of neighbors was combined to create a dichotomous variable *neighborhood social capital*. If participants responded positively concerning both helpfulness of and trust in neighbors, *neighborhood social capital* was categorized as high.

3.3 Statistical methods

In the first publication (Orban et al. 2016), a prospective approach was used to analyze the association of road traffic noise with depressive symptoms after five years of follow-up in participants without depressive symptoms at baseline (n=3,300). We used Poisson regression with a robust variance (Spiegelman and Hertzmark 2005) to estimate crude and adjusted relative risks (RRs) of depressive symptoms after five years in participants with residential road traffic noise >55 db(A) compared to ≤55 db(A). Potential confounding was addressed by adjusting for age, sex, education, income, employment status, neighborhood-level SEP (city unit unemployment rate), traffic proximity, body mass index (BMI), smoking, co-morbidities and insomnia (Orban et al. 2016).

The second paper includes a cross-sectional analysis of the associations between residential surrounding greenness and self-rated health at baseline, as well as of the relationships of both these factors with *neighborhood satisfaction*, *perceived safety*, *social satisfaction* and *neighborhood social capital*. Of the 4,814 baseline participants, 4,480 had complete relevant data and were included in the analysis. A logistic regression model was applied. Odds ratios (OR) for the associations with greenness were calculated for an interquartile range (IQR=0.1) increase in mean NDVI. To account for potential confounding factors, we adjusted for age, sex, employment status, neighborhood-level SEP, household size, BMI and smoking (Orban et al. 2017).

Both papers include additional stratified analyses to study associations in different population subgroups, e.g. by sex, educational level or city of residence. Further, various sensitivity analyses were carried out to explore the robustness of the results. All analyses were conducted with SAS version 9.4 (SAS Institute Inc.).

4 Results

4.1 Road traffic noise and depressive symptoms

In our prospective study (Orban et al. 2016), 302 participants (201 women, 101 men) were classified as having high depressive symptoms after a mean follow-up time of 5.1 years. In total, 35.7% of the participants were exposed to high residential road traffic noise levels (L_{den} >55 dB(A)) at baseline.

As a main result, we found that high depressive symptoms at five-year follow-up were about 30% more frequent in study participants exposed to road traffic noise levels >55 dB(A) compared with ≤55 dB(A), with an adjusted relative risk (RR) of 1.29 (95% confidence interval (CI) 1.03–1.62, model 1) for exposure to >55 versus ≤55 dB(A).

Further, our results offer preliminary evidence that those with a low socioeconomic status and those experiencing sleep disturbances may be particularly vulnerable to road traffic noise effects. Associations were stronger among those who reported insomnia at baseline (RR = 1.62; 1.10–2.59 vs. RR = 1.21; 0.94–1.57 for no insomnia) and appeared to be limited to those with ≤13 years of education (RR = 1.43; 1.10–1.85 vs. 0.92; 0.56–1.53 for >13 years).

Regarding socioeconomic inequalities, we observed differences in the distribution of traffic noise by SEP of the study participants; those with a lower SEP (education, income, unemployed) were more frequently exposed to high traffic noise levels.

The association remained stable after adjustment for various covariates, which underlines the robustness of the results regarding potential confounding. These results provide support to previous studies on the psychological effects of road traffic noise.

4.2 Surrounding greenness, neighborhood environment and social relations, and self-rated health

Results of paper 2 are graphically summarized in Figure 6. In this cross-sectional analysis, we found that a 0.1-increase in residential NDVI (100-m buffer) reduced the odds of poor self-rated health by approximately 10% (adjusted OR = 0.90; 95% CI 0.82–0.98). An increase of 0.1 in NDVI in the 100-m buffer was also associated with high *neighborhood satisfaction* (OR = 1.41; 1.23–1.61) and *neighborhood social capital* (OR = 1.22; 1.12–1.32) in the adjusted model, but not with *perceived safety* (OR = 1.12; 0.86–1.44) and *social satisfaction* (OR = 0.98; CI 0.84–1.15). Magnitude of these associations was similar considering NDVI in a 1000-m buffer. Further, we observed inverse associations of *neighborhood satisfaction* (OR = 0.70; 0.52–0.94), *perceived safety* (OR = 0.36; 0.22–0.60), *social satisfaction* (OR = 0.43; 0.31–0.58) and *neighborhood social capital* (OR = 0.53; 0.44–0.64) with poor self-rated health.

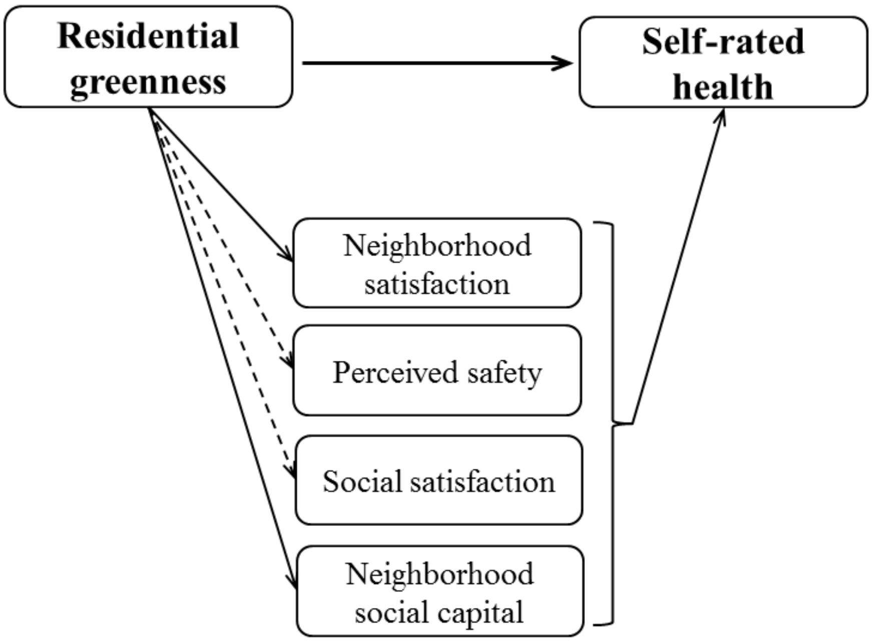


Figure 6 Overview on the observed associations between residential surrounding greenness, self-rated health and neighborhood environment and social variables in this thesis (Orban et al. 2017). Broken lines indicate no association; continued lines indicate an association.

Similar as for road traffic noise, we observed differences in the distribution of residential surrounding greenness by SEP of the study participants; those with lower education (≤13 years) more frequently resided within the lowest quartile of residential greenness (NDVI in 100m ≤0.30) compared to those with higher education. Stratified analyses however indicated no differences in the association between residential greenness and self-rated health by education.

The association between surrounding greenness and self-rated health remained relatively stable after adjustment for various covariates, indicating robustness of the estimates regarding potential confounders.

5 Discussion

The results of the analyses are in line with the presumed health impacts of residential road traffic noise and surrounding greenness and with previous findings, suggesting that exposure to high residential road traffic noise may increase the risk of depressive symptoms, while higher levels of surrounding greenness were associated with better self-rated health. Also, some novel and previously rarely examined aspects were added. In paper 1 (road traffic noise) these aspects primarily consisted of the prospective design in a population-based cohort including men and women, and of stratifying the analyses by e.g. SEP and insomnia. The study in paper 2 (surrounding greenness) not only examined the association between greenness and self-rated health, but additionally associations with participants' subjective perception of neighborhood environment and social factors.

5.1 Strengths and limitations

General strengths of the presented studies include objective measurements of road traffic noise and surrounding greenness, and the availability of geocoded residential addresses to accurately assess individual exposure at the participants' homes. Road traffic noise data from official noise models was used and the NDVI was calculated based on high-quality satellite imagery.

Further, we investigated a large number of randomly selected participants, allowing for associations to be studied in different subgroups. Comprehensive assessment enabled inclusion of many potential confounding factors in our analyses.

Depressive symptoms were measured by a widely used and well established instrument and we further included intake of antidepressant medication in our case definition presented in paper 1. Similarly, the outcome self-rated health analyzed in paper 2 was assessed by a frequently applied and simple instrument which has been shown to well reflect objective health status (Wu et al. 2013).

A further important advantage in the study on road traffic noise and depressive symptoms (Orban et al. 2016) is the prospective design, which allows for investigation of long-term noise effects on the risk of depressive symptoms.

Some main limitations of both papers are linked to the exposure assessment and potential exposure misclassification, a general issue in studies of environmental epidemiology.

Noise exposure assessment in the presented study (Orban et al. 2016) includes residential road traffic noise only; other sources of residential noise, for instance air or railway traffic noise, or noise caused by neighbors, were not included. However, road traffic is considered the major source of noise pollution in urban areas and most of the HNR study population was not affected by aircraft noise. Further, we had no information on time spent at the residence and potential non-residential noise exposures such as occupational noise. Individual characteristics such as room ventilation patterns, hearing ability or noise protection windows were not accounted for in the analysis, but may also contribute to misclassification of noise exposure inside the home. We adjusted for age and employment status, though, which are likely related to time spent at home and thus may reduce potential misclassification bias. Also, traffic noise was modeled for 2006 and the assumption of unchanged noise exposure during the study period may not hold.

For measurements of residential greenness, we used the NDVI (Orban et al. 2017), a quantitative measure that does not provide information about type and 'quality' of the greenness. For example, one cannot distinguish bushes from trees based on the NDVI. Also, the NDVI was measured only around the residence and non-residential exposures to greenness such as park visits, or time spent in other green environments, e.g. during work or leisure time, were not assessed in this study, which may contribute to exposure misclassification. Further, the NDVI can be sensitive to atmospheric conditions, clouds and types of ground cover under the vegetation (Weier and Herring 2000). We aimed to avoid measurement error by choosing satellite data from a cloudless day. Moreover, we used satellite data from the same day (10 July 2003) for all participants, which allows for a comparison of NDVI that does not need to take seasonal variation into account. We relied on a single measurement of NDVI, as the Landsat 5 satellite data we used is only available for few specific dates and varies in quality, e.g. percent cloud cover. However, comparison between our NDVI data and NDVI calculated based on data from 18 July 2006 showed no big differences, so we consider this unlikely to seriously affect our analysis.

For the study focusing on surrounding greenness, self-rated health and neighborhood factors (Orban et al. 2017), the analysis was limited to cross-sectional data. Therefore, the direction of the observed associations cannot be inferred and causal inference is not possible.

A more detailed discussion of the strengths and limitations can be found in the two publications (see Appendix).

5.2 Conclusion and outlook

The results of this thesis add to the existing evidence-base generated through previous research, and further stress the public health relevance of the urban environmental factors road traffic noise and surrounding greenness. Detailed discussions of the findings with regard to the current state of research are included in the respective papers (Orban et al. 2016, 2017).

On the one hand, urban green spaces have been discussed as a psychological buffer for the negative impact of noise pollution on human health (Dzhambov and Dimitrova 2014). On the other hand, green vegetation like trees can also serve as a physical noise barrier, at least to some extent, depending on density and placement (Fang and Ling 2003, 2005). Further, trees can improve the air quality in urban areas (Pugh et al. 2012). Strategically planted trees and vegetation barriers might thus help to reduce the negative health effects of traffic noise, while positively influencing health and well-being through further mechanisms, such as those addressed in the introduction. As we investigated greenness in 100m around the residence, our results for may for example reflect the health benefits of a green 'view from the window' (Honold et al. 2016). From the urban planning perspective, it is important to further examine these interrelationships in experimental and epidemiological studies to identify the most suitable means to enhancing the health benefits of urban environments and create health cities.

Another finding was an association of surrounding greenness and health with *neighborhood satisfaction* and *neighborhood social capital*. While causal relationships cannot be inferred from these results, they highlight the relevance of neighborhood and social aspects in the context of health, and allow for the hypothesis that green residential surroundings can increase neighborhood satisfaction and social capital and thereby contribute to better general health. This should be further investigated in longitudinal studies.

Future studies on greenness and health should also aim to develop methods and tools able to distinguish different 'qualities' of green, and combine qualitative and quantitative measures of green space (Jorgensen and Gobster 2010). Studies on noise and health may extend their exposure assessment from measures of L_{den} or similar dB(A)-based measures to approaches including soundscapes (van Kamp et al. 2016), that consider not only loudness, but also the perceived or measured quality of the acoustic environment.

Further planned projects of the Centre for Urban Epidemiology (CUE) include measuring soundscape metrics in the HNR study area and analyzing joint effects of urban environmental exposures on health. A publication on longitudinal mental health effects of surrounding greenness is also in preparation. First results show an association of higher residential surrounding greenness with less depressive symptoms in the HNR study (unpublished).

6 Summary

The main aim of this thesis was to analyze residential road traffic noise and surrounding greenness in relation to different aspects of human health.

The thesis comprises two publications, which used data from the German Heinz Nixdorf Recall study including 4,814 middle aged and older men and women living in the Ruhr metropolitan region in Germany.

For the first publication, a prospective approach was used to study the effect of residential road traffic noise with depressive symptoms after five years of follow-up in participants that were free from depressive symptoms at baseline. We found that high depressive symptoms occurred about 30% more frequently in study participants exposed to mean annual road traffic noise levels >55 dB(A) compared with ≤55 dB(A), taking relevant potential confounding factors into account.

The second publication comprises a cross-sectional analysis of the association between residential surrounding greenness measured by Normalized Difference Vegetation Index (NDVI) and self-rated health. Further, relationships of greenness and self-rated health with *neighborhood satisfaction*, *perceived safety*, *social satisfaction* and *neighborhood social capital* were analyzed. We found that a 0.1-increase in residential NDVI reduced the odds of poor self-rated health by approximately 10%, considering NDVI both in the 100-m and the 1000-m radius around home and adjusting for potential confounders. Greenness was also positively associated with *neighborhood satisfaction* and *neighborhood social capital* which in turn were also associated with better self-rated health. *Social satisfaction* and *perceived safety* were associated with better self-rated health, but not with residential surrounding greenness measured by NDVI.

The results of this thesis are in line with the presumed health impacts of residential road traffic noise and surrounding greenness and provide support for results that have been reported in previous research. This stresses the importance of the environmental factors traffic noise and surrounding greenness for public health and urban planning. Future studies on these topics should aim to additionally incorporate qualitative measures of environmental exposures.

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8 Appendix

8.1 List of abbreviations

ATC	Anatomical Therapeutic Chemical
BMI	Body mass index
CAPI	Computer-assisted personal interview
CES-D	Center of Epidemiological Studies Depression Scale
CI	Confidence interval
DB(A)	A-weighted decibel
GIS	Geographic Information System
HNR	Heinz Nixdorf Recall (study)
IQR	Interquartile range
L_{den}	Average annual 24-hour (day-evening-night) road traffic noise
L_{night}	Average annual nighttime (6 – 22 h) road traffic noise
NDVI	Normalized Difference Vegetation Index
OECD	Organisation for Economic Co-operation and Development
OR	Odds ratio
RR	Relative risk
SEP	Socioeconomic position
USGS	United States Geological Survey
WHO	World Health Organization

8.2 Paper 1: Road traffic noise and depressive symptoms

Original title: Residential road traffic noise and high depressive symptoms after five years of follow-up: Results from the Heinz Nixdorf Recall study.

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Residential Road Traffic Noise and High Depressive Symptoms after Five Years of Follow-up: Results from the Heinz Nixdorf Recall Study

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Background: Traffic noise affects a large number of people, particularly in urbanized areas. Noise causes stress and annoyance, but less is known about the relationship between noise and depression.

Objective: We investigated the association of residential road traffic noise with depressive symptoms using 5-year follow-up data from a German population-based study.

Methods: We analyzed data from 3,300 participants in the Heinz Nixdorf Recall study who were between 45 and 75 years old and were without depressive symptoms at baseline (2000–2003). Depressive symptoms were defined based on the Center for Epidemiologic Studies Depression scale (CES-D) 15-item questionnaire (total score ≥ 17) and antidepressant medication intake. Road traffic noise was modeled according to European Parliament/Council Directive 2002/49/EC. High noise exposure was defined as annual mean 24-hr noise levels > 55 A-weighted decibels [dB(A)]. Poisson regression with robust variance was used to estimate relative risks (RRs) *a*) adjusting for the potential confounders age, sex, socioeconomic status (SES), neighborhood-level SES, and traffic proximity; *b*) additionally adjusting for body mass index and smoking; and *c*) additionally adjusting for the potential confounders/intermediates comorbidities and insomnia.

Results: Overall, 35.7% of the participants were exposed to high residential road traffic noise levels. At follow-up (mean = 5.1 years after baseline), 302 participants were classified as having high depressive symptoms, corresponding to an adjusted RR of 1.29 (95% CI: 1.03, 1.62; Model 1) for exposure to > 55 versus ≤ 55 dB(A). Adjustment for potential confounders/intermediates did not substantially alter the results. Associations were stronger among those who reported insomnia at baseline (RR = 1.62; 95% CI: 1.10, 2.59 vs. RR = 1.21; 95% CI: 0.94, 1.57) and appeared to be limited to those with ≤ 13 years of education (RR = 1.43; 95% CI: 1.10, 1.85 vs. 0.92; 95% CI: 0.56, 1.53 for > 13 years).

Conclusion: Our results suggest that exposure to residential road traffic noise increases the risk of depressive symptoms.

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Introduction

Noise is a psychosocial stressor that may affect health, even at low levels (Babisch 2002). A large number of people in urban settings are exposed to traffic noise, and the World Health Organization (WHO) considers environmental noise to be an important public health issue (WHO 2011). Beyond causing annoyance, exposure to traffic noise has been associated with stress-related and cardiovascular outcomes such as hypertension and myocardial infarction (Barregard et al. 2009; Fuks et al. 2011; Willich et al. 2005). Recently, an association of long-term exposure to traffic noise with incident diabetes mellitus type 2 has been reported (Sørensen et al. 2013). Until now, epidemiologic research on noise has focused mainly on cardiovascular effects, but less is known about the relationship between traffic noise and mental health problems such as depression.

Depression is a common mental disorder and an increasing public health concern (Weissman et al. 1992), and it is a leading cause of disability worldwide. According to results reported in the Global Burden of Diseases, Injuries, and Risk Factors Study 2010, mental and substance use disorders contributed 7.4% to the total global burden of disease [as measured in disability-adjusted life years (DALYs)] in 2010, of which 40.5% was attributable to depressive disorders (Whiteford et al. 2013). Individuals affected by depression not only experience reduced quality of life due to suffering but also may be unable to cope with everyday life tasks including performing occupational activities, which results in increased sick leave (Wedegaertner et al. 2013).

The etiology of depression is multifactorial and complex. Psychological, social, and biological factors may be involved, most likely in combination (WHO 2012). The potential influence of noise on mental health has been examined, but findings from studies of noise and mental health outcomes have been inconsistent (Crombie et al. 2011; Floud et al. 2011; Hardoy et al. 2005; Niemann et al. 2006; Schreckenberg et al. 2010; Sygna et al. 2014). These discrepancies may be attributed to differences in study design, investigated populations (children, adults), exposures (aircraft and road traffic noise and subjective noise annoyance as opposed to objectively modeled/measured noise), and outcomes (various psychological symptom measures/questionnaires, diagnoses, medication intake, mental hospital admissions). Few studies have examined the association between road traffic noise and depressive symptoms in adults, and there is a particular lack of evidence from prospective studies. To our knowledge, there is only one prospective study that has examined this association (Stansfeld et al. 1996). This study was conducted in Caerphilly, South Wales, and the authors found no association between traffic noise levels at baseline and depression scores after 5 years of follow-up; however, only men (n = 1,725) were included.

There are several proposed pathways supporting the hypothesis that chronic noise exposure may be related to depressive symptoms. Sleep disturbance conditions such as insomnia, which may be caused by traffic noise (Halonen et al. 2012), have been shown to be associated with depression in previous studies (Franzen and Buysse 2008; Riemann

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and Voderholzer 2003; Roberts et al. 2000). Thus, decreased quality of sleep represents one possible link between noise exposure and mental health. A recent cross-sectional study analyzing survey data for 2,778 adults from an age- and sex-stratified population registry sample in Oslo, Norway, found a weak association between road traffic noise and mental health as measured by the Hopkins Symptom Checklist, but only in participants with poor quality of sleep (Sygna et al. 2014). Furthermore, acute noise events cause biological stress reactions (Babisch 2002). Such stress reactions may in turn promote onset of depression (Anisman and Merali 2002; Wager-Smith and Markou 2011); however, single acute noise events are unlikely to cause depression. Thus, the question whether repeated or chronic noise exposure has long-term effects on depressive illness is unresolved.

The aim of this study was to investigate the association of long-term exposure to objectively measured road traffic noise with depressive symptoms within a population-based cohort of middle-aged men and women living in the highly urbanized metropolitan Ruhr area in Germany.

Methods

Study population. We analyzed baseline and 5-year follow-up data from the ongoing prospective Heinz Nixdorf Recall study (HNR) conducted in three large adjacent cities (Bochum, Essen, and Mülheim/Ruhr) located in western Germany. The study design has been described in detail elsewhere (Schmermund et al. 2002). Baseline examinations were performed between 2000 and 2003 and included 4,814 participants between 45 and 75 years old who were randomly selected from population registries. Individuals were eligible if their address was valid, they were not institutionalized, had sufficient knowledge of the German language, were not severely ill, and were able to be interviewed. In addition, pregnant women (although not a priority, given the investigated age group) and relatives of study personnel were excluded. The baseline response calculated as recruitment efficacy proportion was 55.8% (Stang et al. 2005). Follow-up examinations were performed between 2005 and 2008. Our analyzed sample is depicted in Figure 1 and is further described in the statistical analysis section of the "Methods." The study maintains extensive quality management procedures, including a certification according to Deutsches Institut für Normung (DIN) ISO 9001:2000/2008 (DIN 2000). The HNR was approved by the local ethics committees, and all participants gave informed consent prior to participation.

Outcome. Depressive symptoms during the previous week were assessed using the 15-item short-form questionnaire of the Center for Epidemiologic Studies Depression Scale (CES-D) (Hautzinger and Bailer 1993; Radloff 1977), which was distributed to participants at the baseline and 5-year follow-up visits at the study center (and was mailed to participants who did not attend the examinations). The CES-D is a screening tool for measuring depressive symptoms; it has been validated in different populations and settings and is frequently used in health research (Radloff 1977). Possible scores for the 15-item version range from 0 to 45, with higher levels indicating more and/or more frequent depressive symptoms. The CES-D is considered an indicator of a probable depressive episode but does not replace a face-to-face physician diagnosis. Antidepressant medication was also included in the outcome definition because it is indicative of depressive symptoms being treated (even if off-label use may occur) and may affect CES-D results in depressive individuals because treated participants may show fewer symptoms of depression. Assessment of all medication intake was performed by asking participants to bring all medication (including packages) taken in the previous 7 days to both the baseline and follow-up visits. Intake of antidepressant medication classified in the Anatomical Therapeutic Chemical (ATC) groups N06A or N06CA [WHO Collaboration Centre for Drug Statistics Methodology (WHOCC) 2011] and/or a CES-D score ≥ 17 according to Hautzinger and Bailer (1993) were used to define high depressive symptoms.

Exposure. Road traffic noise was modeled according to Directive 2002/49/EC of the European Parliament and Council of the European Union (2002) for the year 2006 as a weighted day–evening–night (24-hr) average sound level (L_{den}) in 5–A-weighted decibel [dB(A)] categories (isophones). The following factors were considered in the noise-level modeling: small-scale topography of the area, dimensions of buildings, noise barriers, street axis, vehicle type–specific traffic density, speed limit, and type of road surface. Noise exposure data were assigned to the geographic residence location of the study participant at baseline using the geographic information system ArcGIS, assuming average noise levels to be relatively stable over time. High noise exposure was defined as noise levels of L_{den} > 55 dB(A), based on the maximum community noise levels recommended by the WHO (Berglund et al. 1999). Data on nighttime noise (L_{night}, 2200–0600 hours) were available and were also analyzed, with nighttime noise levels > 50 db(A) defined as high noise exposure.

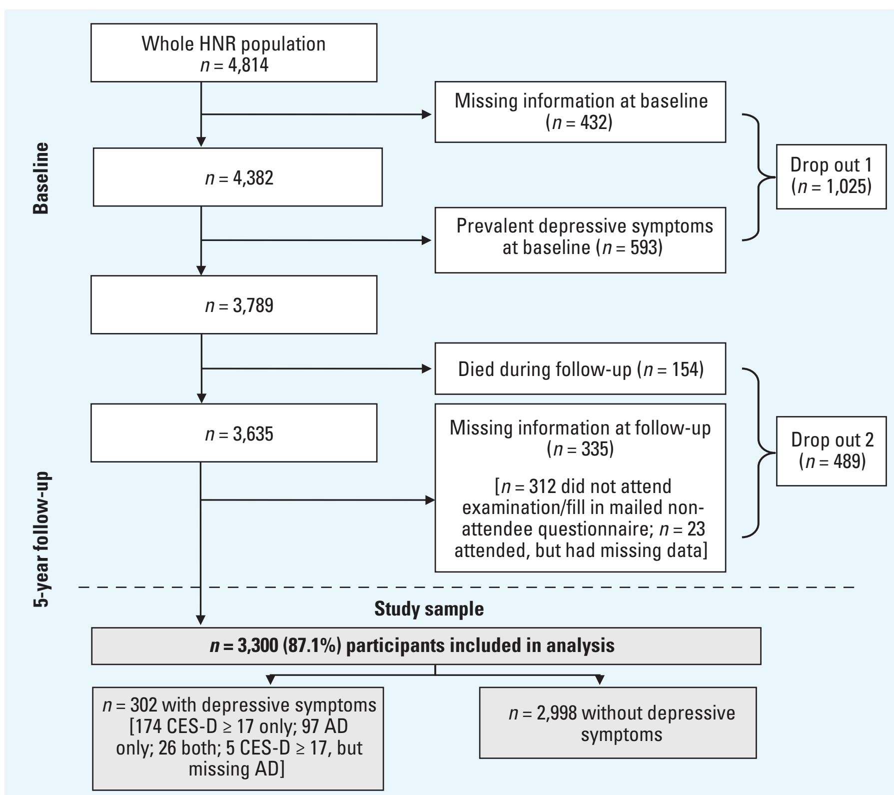

Figure 1. Flow chart of study participants in the Heinz Nixdorf Recall (HNR) study. Missing information = missing information on depressive symptoms [Center for Epidemiologic Studies Depression Scale (CES-D), antidepressant medication use (AD)]; prevalent depressive symptoms = CES-D ≥ 17 and/or antidepressant medication use.

Covariates. Socioeconomic (e.g., income), demographic (e.g., age), behavioral (e.g., smoking: current, former, or never smoker), and medical history data were assessed via standardized computer-assisted personal interviews at the baseline examination. Education, income, and economic activity were used as indicators of socioeconomic status (SES) (Shavers 2007; Galobardes et al. 2007). Education was defined by combining school and vocational training as total years of formal education, according to the International Standard Classification of Education (UNESCO 1997), and was categorized into four groups (≤ 10, 11–13, 14–17, and ≥ 18 years). Income was measured as the monthly household equivalent income, which was calculated by dividing the total household net income by a weighting factor for each household member, and was divided into four groups using sex-specific quartiles. Economic activity was categorized into three groups [employed, inactive (retired, homemaker, etc., but not unemployed), and unemployed]. Information on whether participants had/had ever had myocardial infarction, heart failure, stroke, diabetes mellitus, emphysema, asthma, cancer, rheumatism, slipped disc, or migraine (yes/no) at baseline was used to create a categorical variable indicating the number of comorbidities (0, 1, or ≥ 2). In addition, participants were asked to indicate if they had/had ever had depression. Insomnia was assessed based on three insomnia symptoms: difficulties falling asleep, difficulties maintaining asleep, and early morning arousals (Riedel et al. 2012). If participants reported that all of these symptoms were present at least two times per week during the previous 4 weeks, they were classified as having insomnia. One example of the three insomnia questions is "How often, during the last 4 weeks, did you have difficulties in falling asleep?" The possible answers were "never," "sometimes (one time per week or less)," "often (at least 2 times per week)," or "almost every night." Height and weight were obtained from standardized anthropogenic measurements performed during the clinical examination. The body mass index (BMI) was calculated as [weight in kilograms/(height in meters)^2].

We applied the 2001 unemployment rate in the respective city unit (German terms: in Essen, "Stadtteil"; in Bochum and Mülheim/Ruhr, "Statistischer Bezirk") as an indicator of neighborhood-level SES. These data were obtained from the local census authorities of the respective cities of Bochum, Essen, and Mülheim/Ruhr.

Residential distance to the nearest major road was calculated as a marker of traffic proximity using ArcGIS. A major road was defined as one falling into the upper quartile of mean daily traffic density (> 22,980 vehicles per day, year 2000). There was a weak negative correlation between traffic proximity and noise in our study (Pearson $r = -0.22$). We included this variable in the analysis to control for nonacoustic factors of traffic and the physical environment of the neighborhood (e.g., aesthetic aspects and perceived safety) that might affect mental wellbeing.

Statistical analyses. From the full HNR sample ($n = 4{,}814$), we excluded 432 participants with missing information on depressive symptoms (CES-D and/or antidepressant medication) and an additional 593 participants with prevalent high depressive symptoms at baseline (Figure 1). Of the remaining 3,789 participants, 154 died during follow-up, 312 were excluded because they did not attend the follow-up examination (when medication use and CES-D were assessed) or complete the mailed nonattendee follow-up questionnaire (including the CES-D), and 23 were excluded because they did not complete the CES-D and were not identified as using antidepressant medication at the follow-up visit (Figure 1). Five of the included participants did not attend the follow-up visit but were classified as having high depressive symptoms based on the mailed nonattendee follow-up CES-D. Thus, the final analysis sample included 3,300 participants (87.1% of the 3,789 eligible participants).

We used Poisson regression with a robust variance to estimate crude and adjusted effects of high road traffic noise on depressive symptoms after 5 years (Spiegelman and Hertzmark 2005; Zou 2004). The adjustment sets were selected *a priori* based on a directed acyclic graph (see Supplemental Material, Figure S1) created with DAGitty (Textor et al. 2011). In model 1, we adjusted for age (continuous), sex, education (four categories), income (quartiles), economic activity (three categories), neighborhood-level SES (unemployment rate, continuous) and traffic proximity (continuous). In Model 2, we additionally adjusted for the potential confounders BMI (continuous) and smoking, and in Model 3, the potential confounders/intermediates comorbidities (0, 1, or ≥ 2) and insomnia (yes/no) were added. Observations with any missing covariate data were automatically excluded from the respective analysis (complete case analysis). All analyses were also stratified by sex to investigate potential sex-specific differences. In addition to modeling road traffic noise as a binary variable [$L_{den} > 55$ vs. ≤ 55 dB(A)], we estimated associations with three noise exposure categories [$L_{den} > 55$ to ≤ 60 dB(A), > 60 to ≤ 65 dB(A), > 65 dB(A)] compared with the reference group that had $L_{den} \leq 55$ dB(A) noise exposure.

We conducted exploratory analyses by stratifying the participants by *a*) education level (≤ 13 vs. > 13 years of formal education), *b*) movers versus nonmovers between the baseline and 5-year follow-up visits, *c*) insomnia (yes/no), and *d*) city of residence. Further sensitivity analyses were conducted by *e*) additionally excluding participants who reported to have/ever have had depression at baseline, *f*) using a cutoff of $L_{den} > 65$ dB(A) to define very high noise exposure, *g*) using CES-D score ≥ 17 exclusively to define high depressive symptoms at baseline and follow-up, and *h*) using antidepressant medication intake exclusively to define high depressive symptoms at baseline and at follow-up.

All analyses were conducted with SAS v.9.4 (SAS Institute Inc.).

Results

Baseline characteristics of the analyzed population by noise exposure are shown in Table 1. Participants with high and low noise exposure were similar regarding sex and mean age, whereas proportions of insomnia, low education, low income, unemployment, and active smoking were higher in participants exposed to high noise levels. Only a small amount of covariate data were missing (maximum 15, for insomnia), with the exception of the income variable, for which a total of 196 values were missing (Table 1). Additionally, 605 values were missing for the variable indicating reported (lifetime) prevalence of depression, which was applied in one of the sensitivity analyses. At follow-up (5.1 years after baseline, on average), 302 participants [9.2%, including 201/1,585 women (12.7%) and 101/1,715 men (5.9%)] were classified as having high depressive symptoms based on a CES-D score ≥ 17 ($n = 179$), use of antidepressant medication ($n = 97$), or both ($n = 26$) in the previous week (Figure 1). Participants who were excluded from the analysis because of depressive symptoms/missing depressive symptoms data at baseline (drop out 1), or death or missing outcome data at follow-up (drop out 2), were similar to the analysis sample with regard to sex, age, and other baseline characteristics (see Supplemental Material, Table S1). However, they were more likely to have been current smokers (26–31% vs. 20–24%), and they had more comorbidities (36–37% vs. 29–31% with ≥ 2), lower education (19% vs. 8–9% with ≤ 10 years), and lower income (33–34% vs. 21–27% in the lowest quartile) than participants who were included in the analysis. Participants excluded because of prevalent depressive symptoms at baseline/missing depressive symptoms data were more likely to have reported insomnia at baseline (22% vs. 8–11%) and were less likely to be male (40% vs. 52%) than those who were included.

Of the included study population, 35.7% ($n = 1{,}179$) were exposed to high 24-hr traffic noise levels [$L_{den} > 55$ dB(A)], and 25.8% ($n = 850$) were exposed to high traffic noise at night [L_{night} > 50 dB(A)]. Distributions of annual mean noise exposures (overall and at night) were positively skewed (see Supplemental Material, Figure S2).

The results of the regression analysis (Table 2) revealed an adjusted RR (Model 1) of 1.29 (95% CI: 1.03, 1.62) for high depressive symptoms at follow-up in participants exposed to high noise levels compared with the low-noise exposure group. Estimates for men and women combined were similar for Models 2 and 3 and the unadjusted estimate (Table 2). Unadjusted associations were stronger for men than for women but were similar between men and women after adjustment for sociodemographic covariates (Model 1) and BMI and smoking (Model 2). Adjusting for potential intermediates (comorbidities and insomnia, Model 3) slightly reduced the RR toward the null for men but did not influence the association for women. We excluded participants with missing income data (*n* = 196), which produced no substantial influence on the results, yielding a crude total RR of 1.39 (95% CI: 1.11, 1.74; *n* = 3,104) and an RR of 1.43 (95% CI: 0.97, 2.10; *n* = 1,652) in men and an RR of 1.36 (95% CI: 1.03, 1.78; *n* = 1,452) in women (data not shown in Table 2). In general, associations between depression and exposure to noise at night [L_{night} > 50 vs. ≤ 50 dB(A)] were similar to associations with average 24-hr noise exposure (Model 1 RR = 1.29; 95% CI: 1.01, 1.64 for men and women combined), although associations were weaker for men (RR = 1.19; 95% CI: 0.77, 1.82) than for women (RR = 1.36; 95% CI: 1.01, 1.82) (see Supplemental Material, Table S2).

Associations between noise and depressive symptoms did not increase with increasing noise when exposure was categorized into four groups (Figure 2). When compared with the ≤ 55 dB(A) category, the association was strongest for the middle exposure category [> 60 to ≤ 65 dB(A), RR = 1.52; 95% CI: 1.11, 2.07] and equally weaker for the highest and lowest exposure groups (RR = 1.19; 95% CI: 0.85, 1.68 and RR = 1.19; 95% CI: 0.86, 1.65, respectively) (Figure 2). Similarly, there was no evidence of a monotonic dose–response relationship for nighttime road traffic noise, but the pattern differed: the middle exposure category [> 55 to ≤ 60 dB(A)] had the weakest association compared with the ≤ 50 dB(A) reference

Table 1. Characteristics of the analyzed Heinz Nixdorf Recall study population (*n* = 3,300), by 24-hr road traffic noise.

Characteristic	L_{den} > 55 dB(A) *n* (percent), mean ± SD, or median (Q1, Q3)	L_{den} ≤ 55 dB(A) *n* (percent), mean ± SD, or median (Q1, Q3)
Baseline		
n (percent)	1,179 (35.7)	2,121 (64.3)
Men	610 (51.7)	1,105 (52.1)
Age (years)	59.1 ± 7.7	59.3 ± 7.6
Insomnia	124 (10.5)	177 (8.4)
Missing (*n*)	3	12
Number of comorbidities[a]		
0	440 (37.3)	830 (39.1)
1	374 (31.7)	687 (32.4)
≥ 2	365 (31.0)	604 (28.5)
Reported (lifetime) prevalence of depression	70 (7.3)	106 (6.1)
Missing (*n*)	225	380
Body mass index	27.9 ± 4.7	27.7 ± 4.5
Missing (*n*)	6	4
Smoking		
Current	288 (24.4)	423 (19.9)
Former	419 (35.5)	778 (36.7)
Never	472 (40.0)	920 (43.4)
Distance to nearest major road (meters)	532.4 (220.0,1083.1)	987.7 (552.8,1620.7)
Missing (*n*)	0	5
Unemployed in neighborhood (percent)	12.8 ± 3.3	12.0 ± 3.3
Education (years)[b]		
≤ 10	111 (9.4)	165 (7.8)
11–13	703 (59.6)	1,135 (53.5)
14–17	251 (21.3)	525 (24.8)
≥ 18	114 (9.7)	295 (13.9)
Missing (*n*)	0	1
Household net income		
Quartile 1 (low)	300 (27.0)	420 (21.1)
Quartile 2	257 (23.1)	473 (23.8)
Quartile 3	290 (26.1)	502 (25.2)
Quartile 4 (high)	266 (23.9)	596 (29.9)
Missing (*n*)	66	130
Economic activity		
Employed	503 (42.7)	937 (44.2)
Inactive	591 (50.2)	1,078 (50.8)
Unemployed	84 (7.1)	106 (5.0)
Missing (*n*)	1	0
City of residence		
Mülheim/Ruhr	467 (39.6)	772 (36.4)
Bochum	334 (28.3)	654 (30.8)
Essen	378 (32.1)	695 (32.8)
Follow-up		
CES-D ≥ 17 and/or antidepressant medication	127 (10.8)	175 (8.3)
CES-D ≥ 17	89 (7.6)	116 (5.5)
Antidepressant medication	56 (4.8)	67 (3.2)
Missing (*n*)[c]	2	3
Moved between baseline and follow-up		
Yes	214 (18.2)	314 (14.8)
No	965 (81.9)	1,807 (85.2)

Abbreviations: CES-D, Center for Epidemiologic Studies Depression Scale; dB(A), A-weighted decibels; L_{den}, average annual 24-hour noise level; Q1, quartile 1 (25th percentile); Q3, quartile 3 (75th percentile).
[a]Of the following: myocardial infarction, heart failure, stroke, diabetes, emphysema, asthma, cancer, rheumatism, slipped disc, migraine. [b]Combines school and vocational training. [c]These participants were identified as having high depressive symptoms by CES-D and were therefore included.

Table 2. Relative risks (with 95% confidence intervals) of high depressive symptoms at follow-up in study participants exposed to residential road traffic noise (L_{den}) > 55 dB(A) and L_{den} ≤ 55 dB(A).

Model	Cases (*n*)	Total (*n*)[a]	RR (95% CI)
Unadjusted			
Total	302	3,300	1.31 (1.05, 1.62)
Men	101	1,715	1.46 (1.00, 2.13)
Women	201	1,585	1.23 (0.95, 1.60)
Model 1[b]			
Total	279	3,098	1.29 (1.03, 1.62)
Men	98	1,650	1.29 (0.87, 1.92)
Women	181	1,448	1.30 (0.98, 1.72)
Model 2[c]			
Total	278	3,089	1.28 (1.02, 1.61)
Men	98	1,644	1.28 (0.85, 1.94)
Women	180	1,445	1.28 (0.97, 1.69)
Model 3[d]			
Total	276	3,075	1.26 (1.00, 1.58)
Men	97	1,637	1.21 (0.81, 1.82)
Women	179	1,438	1.28 (0.97, 1.70)

Abbreviations: CI, confidence interval; dB(A), A-weighted decibels; RR, relative risk.
[a]Numbers in Models 1-3 differing from the unadjusted model reflect missing covariate data. [b]Adjusted for age, sex (except in the sex-stratified analysis), education, income, economic activity, neighborhood-level socioeconomic status, traffic proximity. [c]Additionally adjusted for body mass index, smoking. [d]Additionally adjusted for comorbidities, insomnia.

group (RR = 1.14; 95% CI: 0.78, 1.65) (see Supplemental Material, Figure S3).

Table 3 shows the results of additional analyses. We estimated a positive association between noise exposure and high depressive symptoms at follow-up among 2,115 participants with ≤ 13 years of education (Model 1 RR = 1.43; 95% CI: 1.10, 1.85), in contrast with a weak negative association among 1,185 participants with > 13 years of education (RR = 0.92; 95% CI: 0.56, 1.53). A higher effect estimate was found in the subgroup with insomnia at baseline (Model 1 RR = 1.62; 95% CI: 1.01, 2.59; n = 281) than in those without insomnia at baseline (RR 1.21; 95% CI: 0.94, 1.57; n = 2,803) (Table 3). The association between traffic noise and depressive symptoms did not change remarkably when excluding participants who reported to have/ever have had depression at baseline (n = 176) or had missing data on depression (n = 605), yielding an RR of 1.24 (95% CI: 0.97, 1.59; Model 1). Using a higher cutoff value for defining high noise exposure [L_{den} > 65 vs. ≤ 65 dB(A)] resulted in an RR of 1.07 (95% CI: 0.77, 1.49), which is in accord with the results shown in Figure 2. Using either only a CES-D score ≥ 17 (n = 244 cases at follow-up) or only intake of antidepressant medication (n = 157 cases at follow-up) to define the outcome did not produce results that were different from those obtained with the combined outcome definition (Table 3). In general, additional analyses for the association of nighttime traffic noise exposure > 50 dB(A) versus ≤ 50 dB(A) with high depressive symptoms at follow-up showed similar results to those for 24-hr noise exposure, with the possible exception of the analysis that used antidepressant medication use to define outcome (see Supplemental Material, Table S3).

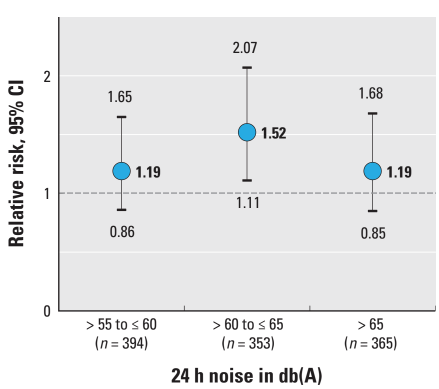

Figure 2. Relative risks and 95% confidence intervals of high depressive symptoms at follow-up in association with exposure to different categories of 24-hr noise compared with the lowest noise category [≤ 55 dB(A); n = 1,986], adjusted for baseline age, sex, education, income, economic activity, neighborhood-level socioeconomic status, and traffic proximity (Model 1). dB(A), A-weighted decibels.

Discussion

Our prospective study provides support for the hypothesis that long-term exposure to road traffic noise may increase the risk of depressive symptoms.

In our study population as a whole, high depressive symptoms at follow-up were ~25–30% more frequent in study participants exposed to road traffic noise levels > 55 dB(A) than in participants exposed to noise levels ≤ 55 dB(A). The association remained stable after adjustment for various covariates, highlighting the robustness of the results when considering potential confounding factors. Our findings are in line with results from previous cross-sectional studies on road traffic noise and depression. A study conducted in Serbia (Stošić and Blagojević 2011) with 911 participants between 18 and 80 years old found that participants living in a noisy city area of Niš [daily period noise ≥ 55 dB(A) and night noise ≥ 45 dB(A)] reported "feeling depressed" more frequently than the control participants, who lived in two quiet city areas [daily period noise ≤ 55 dB(A) and night noise ≤ 45 dB(A)]. A similar small Swedish study compared 151 persons who lived in a quiet city area with 97 persons who lived in an area exposed to noise (Öhrström 1991). The study used mailed questionnaires to assess psychosocial wellbeing, including depression, and the authors found that people living in the noisy area felt depressed more often. In another questionnaire-based study of 366 women (20–60 years old) living in Tokyo (Yoshida et al. 1997), an unadjusted OR of 2.9 (p < 0.05) for high responses to depression-related questions was found for women exposed to residential road traffic noise levels > 70 dB(A) compared with those exposed to 45 to ≤ 70 dB(A). Importantly, none of these cross-sectional studies reported controlling for potential confounding factors. Sygna et al. (2014) found an association (controlled for confounders) between road traffic noise and psychological distress, including depressive symptoms, but only in a subgroup of 274 participants with low sleep quality (OR 1.40, 95% CI: 0.99, 1.98; per 10-dB increase). To our knowledge, the Caerphilly study (Stansfeld et al. 1996) is the only previous prospective study of traffic noise and depressive symptoms; in this study, the authors analyzed data from 1,725 men living in Caerphilly, South Wales (50–64 years old). This men-only study found no association between traffic noise levels at baseline [in four 5-dB(A) categories ranging from 51–55 dB(A) to 66–70 dB(A)] and mean depression scores from the general health questionnaire at the 5-year follow-up, adjusting for age, social class, noise sensitivity, and depressive symptoms at baseline (n = 1,587). However, the study did find an association with mean anxiety scores, which significantly differed across the noise categories (p for heterogeneity = 0.03, n = 1,584) (Stansfeld et al. 1996). In summary, most previous studies on road traffic noise and depressive symptoms found an association, and our study adds to the existing body of evidence by prospectively analyzing a comprehensive cohort including both men and women while at the same time accounting for potential confounding factors.

Sex-specific analyses revealed no differences between men and women. It is notable,

Table 3. Results of the sensitivity analyses, showing relative risks (with 95% confidence intervals) of high depressive symptoms at follow-up in study participants exposed to residential road traffic noise (L_{den}) > 50 dB(A) and ≤ 50 dB(A).

Subgroup	Cases (n)	Total (n)[a]	RR (95% CI)[b]
Education			
≤ 13 years	214	1,968	1.43 (1.10, 1.85)
> 13 years	65	1,130	0.92 (0.56, 1.53)
Moved during follow-up			
Yes	61	502	1.17 (0.72, 1.88)
No	218	2,596	1.33 (1.02, 1.72)
Insomnia			
Yes	55	281	1.62 (1.01, 2.59)
No	222	2,803	1.21 (0.94, 1.57)
City of residence			
Mülheim/Ruhr	99	1,162	1.21 (0.83, 1.76)
Bochum	89	927	1.51 (1.00, 2.29)
Essen	91	1,009	1.16 (0.77, 1.74)
Excluded lifetime prevalence of depression at baseline[c]	189	2,382	1.34 (1.01, 1.76)
Noise cutoff L_{den} > 65 dB(A)	279	3,098	1.07 (0.77, 1.49)
CES-D ≥ 17 only to define outcome	227	3,469	1.24 (0.96, 1.61)
Antidepressant medication only to define outcome	144	3,467	1.28 (0.92, 1.80)

Abbreviations: CES-D, Center for Epidemiologic Studies Depression Scale; CI, confidence interval; dB(A), A-weighted decibels; RR, relative risk.
[a]Maximum total n in Model 1 = 3,098; numbers differing from those in Table 1 reflect missing covariate data (in Model 1). [b]Adjusted for age, sex, education (not in the education-stratified analysis), income, economic activity, neighborhood-level socioeconomic status, and traffic proximity (Model 1). No substantial differences were observed in unadjusted results and in results for Model 2 and Model 3 (data not shown). [c]Excluded 176 participants who reported having/having ever had depression and 605 participants with missing data.

however, that high depressive symptoms at follow-up were far more common in women than in men (12.7% vs. 5.9%). This result is consistent with existing epidemiologic research, where a higher prevalence of depression has been observed in women than in men, with an estimated female:male ratio of 2.3 (Wittchen et al. 2011). It has been argued that these differences in prevalence may not be real because depression symptoms may vary between men and women (Azorin et al. 2014; Rutz 1999; Schuch et al. 2014), but commonly applied diagnostic criteria focus on symptoms that are rather typical for women, and men are believed to display less pronounced help-seeking behavior than women (Piccinelli and Wilkinson 2000; Schuch et al. 2014). Thus, a potential for measurement error caused by sex-insensitive diagnostic criteria and varying prescribing patterns must be considered, and sex-specific associations deserve further attention.

When investigating different categories of road traffic noise, RRs did not increase linearly with increasing noise levels, and we found that elevated risks of high depressive symptoms were strongest not in the highest exposure group but in the intermediate exposure group for 24-hr noise exposure. However, the number of participants in the noise categories was small, the overall incidence of depressive symptoms was low, and we consider this analysis primarily exploratory for future research aims. Previous studies also failed to identify a linear trend (Stansfeld et al. 1996; Yoshida et al. 1997). An explanation for this missing dose–response relationship may be that measures for noise mitigation (e.g., noise protection windows) and behavioral prevention (i.e., closed windows, choice of quiet sleeping room, earplugs) may be more common in areas with very high noise exposure. A nonlinear relationship of exposure and outcome may also contribute to the inconsistency among the results from previous studies.

We found a strong association of traffic noise with high depressive symptoms in less-educated participants and a weak negative association in highly educated participants (Table 3). Furthermore, a high proportion of study participants with low incomes and low education and who were unemployed had high traffic-noise exposure (Table 1), supporting previous observations of a socially inequitable distribution of environmental burden (Braubach and Fairburn 2010). A previous analysis performed by the German Socio-Economic Panel found that low household income was associated with high perceived noise exposure (Kohlhuber et al. 2006).

The association of noise with depression-related outcomes that was observed in the HNR and in previous studies seems to be biologically plausible. Stratified analyses in the present study revealed a strong association between high noise exposure and high depressive symptoms in participants with insomnia at baseline, and the same was found in a previous study (Sygna et al. 2014). This finding is in line with the hypothesis of impaired sleep as a possible pathway for developing depressive symptoms (Baglioni et al. 2011). However, insomnia may also be a symptom of depression rather than a contributing factor; thus, an association between depression and insomnia at the same point in time may be bidirectional. Our results suggest that individuals with preexisting sleep disturbances might have increased vulnerability to the effects of noise on depressive symptoms. However, we do not know the underlying causes of insomnia in our study population.

Another factor linking noise and depression may be noise-induced stress reactions of the body. Acute noise stimuli cause the central nervous system to initiate warning/alert reflexes that are beyond individual control and that affect a number of bodily functions, such as muscle tension and pulse rate (Rylander 2004). Repeated exposure to noise for long periods is typically considered unpleasant or annoying when it interferes with activities of living such as communication, tasks that require concentration, or recreational activities such as sleep and rest. Habituation to noise rarely occurs, and chronic exposure to noise that causes negative physiological stress reactions may lead to a stage where acute effects, such as increased blood pressure, become permanent (Rylander 2004). Furthermore, it has been noted that exposure to stressors promotes neurochemical and endocrine changes that may be involved in the provocation of depressive disorder (Anisman and Merali 2002; Wager-Smith and Markou 2011). Chronic stress caused by noise exposure may lead to involuntary defeat reactions characterized by, for example, decreased motor function, reduced secretion of cortisol and adrenaline, and suppression of the immune system, with depression of mood a possible consequence. However, the extent to which noise causes such defeat reactions may differ among individuals depending on the ability to escape noise by, for example, closing the windows or choosing a bedroom facing away from the street (Rylander 2004). Increased stress hormone levels caused by noise are a frequent finding (Ising and Kruppa 2004) and may explain our observed results when we considered physiological stress as a factor in the pathway from noise exposure to depression. It is also possible that the observed association of noise with depressive symptoms is in part mediated by other stress-related or chronic diseases such as cardiovascular disease, which has been found to be associated with both noise and depression (Münzel et al. 2014; Hare et al. 2014); however, accounting for comorbidities by adjustment did not change the RR estimate in our study.

Strengths of this study include a high-quality noise exposure model and residential addresses obtained at baseline to accurately assess exposure. Depressive symptoms were assessed by a widely used and well-established instrument. The prospective design allowed investigation of long-term noise effects, assuming that the mean noise levels modeled for 2006 and assigned to the baseline (2000–2003) residence location were constant over the 5-year follow-up period. We were able to investigate a large number of randomly selected participants, allowing noise effects to be studied in different subgroups. Furthermore, comprehensive measurements enabled inclusion of many potential confounding factors in our analyses.

With regard to study limitations, exposure misclassification is a major concern in environmental epidemiology. Noise exposure assessment in the present study included residential road traffic noise only; other sources of residential noise, such as air or railway traffic noise or noise caused by neighbors, were not included. Nevertheless, road traffic is considered the major source of noise pollution in urban metropolitan contexts such as the investigated Ruhr area (Omidvari and Nouri 2009), and most of the neighborhoods included in our study population were not affected by aircraft noise. Furthermore, we had no information on time spent at the residence or on nonresidential noise exposures such as occupational noise. Individual characteristics such as room ventilation patterns, hearing ability, and noise protection windows were not accounted for in the analysis but may also have contributed to misclassification of noise exposure. Participants with (very) high levels of noise exposure may make more use of noise-avoidance strategies, which may lead to an underestimation of the effect that would be observed without these measures. This may in part explain our findings of a lower RR in the highest noise category. Participants exposed to high and low levels of noise may differ in some characteristics relevant to the development of depressive symptoms, and although we were able to take a range of these factors into account in our analyses, unknown confounding cannot be ruled out. Additional bias caused by missing data is possible; however, income information was the most commonly missing data, yet excluding those missing data from the crude model did not change the results. Potential air pollution effects were only accounted for indirectly by adjusting for traffic proximity. Modeling the average noise level, as we did here, does not reflect potential peaks, extreme noise events, or single sleep-disturbing noise events in otherwise quiet areas, all of which are of special relevance in terms of physiological stress reactions to noise (Rylander 2004; Babisch 2002). In addition, noise was modeled for the year 2006, and the assumption of unchanged noise exposure during the study period may not hold. The severity and presence of depressive symptoms vary over time; therefore, additional CES-D assessments (e.g., yearly instead of every 5 years) would have allowed for a more precise outcome measurement. We investigated a general population sample of middle-aged and older men and women living in a German metropolitan area; hence, our results cannot be generalized to populations from other countries, to children or young adults, or to populations residing in rural areas.

Conclusion

Our results suggest that exposure to residential traffic noise may increase the risk of high depressive symptoms in middle-aged and older adults. Additionally, our study offers preliminary evidence that those with low socioeconomic status and those who experience sleep disturbances may be particularly vulnerable to noise effects. Further prospective research is needed to confirm the results of our study and to extend the generalizability of our findings to other populations. Studies including measures of stress and subjective noise annoyance may also extend our knowledge into the mechanisms of noise-induced depression. However, there is already evidence of adverse health effects arising from noise exposure, stressing the necessity of protecting populations from noise pollution; this is particularly important with regard to environmental justice because our results indicate that traffic noise may be unequally distributed across social strata.

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Supplemental Material

Residential Road Traffic Noise and High Depressive Symptoms after Five Years of Follow-up: Results from the Heinz Nixdorf Recall Study

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Table S1 Characteristics of the Heinz Nixdorf Recall study participants that were excluded from our analysis.

Drop out 1 refers to those excluded due to missing information on depressive symptoms (CES-D, antidepressant medication use) or prevalent depressive symptoms (CES-D ≥17 and/or antidepressant medication use) at baseline. Drop out 2 refers to participants who died between baseline and follow-up, or had insufficient information on CES-D/antidepressant medication use to assess depressive symptoms at follow-up (see also table 1).

Characteristics	**Drop out 1 (N=1,025)**	**Drop out 2 (N=489)**
	N (%), mean ± SD, or median (Q1, Q3)	N (%), mean ± SD, or median (Q1, Q3)
Baseline		
Exposed to L_{den} >55 dB(A)	354 (34.5)	186 (38.0)
Exposed to L_{night} >50 dB(A)	243 (23.3)	138 (28.2)
Men	411 (40.1)	269 (55.0)
Age (years)	59.6 ± 8.0	62.2 ± 8.3
CES-D ≥17 and/or antidepressant medication	593 (100.0)	0 (0.0)
N missing	432	0
CES-D ≥17	449 (52.5)	0 (0.0)
N missing	169	0
Antidepressant medication	221 (31.1)	0 (0.0)
N missing	314	0
Insomnia	220 (21.8)	54 (11.3)
N missing	17	10
Number of co-morbidities[b]		
0	366 (35.7)	155 (31.7)
1	295 (28.8)	155 (31.7)
≥ 2	364 (35.5)	179 (36.6)
Reported lifetime prevalence of depression	213 (24.5)	36 (8.9)
N missing	157	86
Body mass index	28.2 ± 4.8	28.4 ± 4.6
N missing	17	2
Smoking		
current	268 (26.3)	149 (30.7)
former	304 (29.9)	161 (33.1)
never	446 (43.8)	176 (36.2)
N missing	7	3
Distance to nearest major road (meters)	811.6 (428.1, 1400.1)	859.2 (407.2, 1507.0)
N missing	3	1
Unemployed in neighborhood (%)	13.0 ± 3.7	12.9 ± 3.5
Education[d]		
≤ 10 years	194 (18.9)	92 (18.8)
11–13 years	576 (56.2)	262 (53.6)

(Table S1 continued)

14–17 years	181 (17.7)	111 (22.7)
≥ 18 years	74 (7.2)	24 (4.9)
N missing	0	1
Household net income		
Quartile 1 (low)	318 (33.8)	149 (32.5)
Quartile 2	217 (23.1)	111 (24.2)
Quartile 3	229 (24.3)	107 (23.3)
Quartile 4 (high)	177 (18.8)	92 (20.0)
N missing	84	30
Economic activity		
employed	354 (34.9)	132 (27.6)
inactive	567 (55.9)	330 (67.9)
unemployed	93 (9.2)	22 (4.5)
N missing	11	3
City of residence		
Mülheim	355 (34.7)	163 (33.3)
Bochum	270 (26.4)	142 (29.0)
Essen	399 (39.0)	184 (37.6)
Follow-up		
CES-D ≥17 and/or antidepressant medication	308 (36.8)	0 (0.0)
N missing	188	489
CES-D ≥17	226 (26.8)	0 (0.0)
N missing	180	441
Antidepressant medication	140 (16.7)	0 (0.0)
N missing	186	466

Q1 and Q3= quartile 1 (25th percentile) and quartile 3 (75th percentile)

[a] Of the following: myocardial infarction, heart failure, stroke, diabetes, emphysema, asthma, cancer, rheumatism, slipped disc, migraine

[b] Combining school and vocational training

Table S2 Relative risks (with 95% confidence intervals) of high depressive symptoms at follow-up in study participants exposed to residential nighttime road traffic noise (L_{night}) >50 dB(A) compared with ≤50 dB(A).

Model	N cases	N total	RR (95% CI)
Unadjusted			
total	302	3,300	1.30 (1.03, 1.64)
men	101	1,715	1.31 (0.87, 1.97)
women	201	1,585	1.31 (0.99, 1.73)
Model 1[a]			
total	279	3,098	1.29 (1.01, 1.64)
men	98	1,650	1.19 (0.77, 1.82)
women	181	1,448	1.36 (1.01, 1.82)
Model 2[b]			
total	278	3,089	1.30 (1.02, 1.65)
men	98	1,644	1.19 (0.76, 1.86)
women	180	1,445	1.37 (1.02, 1.83)
Model 3[c]			
total	276	3,075	1.29 (1.01, 1.64)
men	97	1,637	1.14 (0.74, 1.76)
women	179	1,438	1.39 (1.03, 1.86)

[a] Adjusted for age, sex (except in the sex-stratified analysis), education, income, economic activity, neighborhood-level socioeconomic status, traffic proximity
[b] Additionally adjusted for body mass index, smoking
[c] Additionally adjusted for co-morbidities, insomnia

Table S3 Results of the sensitivity analyses, showing relative risks (with 95% confidence intervals) of high depressive symptoms at follow-up in study participants exposed to residential nighttime road traffic noise (L_{night}) >50 dB(A) compared with ≤50 dB(A).

Subgroup	**N cases**	**N total**[a]	**RR (95% CI)**[b]
Education			
≤13 years	214	1,968	1.38 (1.05, 1.81)
>13 years	65	1,130	1.01 (0.57, 1.79)
Moved during follow up			
yes	61	502	1.34 (0.82, 2.20)
no	218	2,596	1.27 (0.96, 1,68)
Insomnia			
yes	55	281	1.56 (0.96, 2.52)
no	222	2,803	1.24 (0.94, 1.63)
City of residence			
Mülheim/R	99	1,162	1.26 (0.85, 1,87)
Bochum	89	927	1.36 (0.88, 2.11)
Essen	91	1,009	1.23 (0.79, 1.90)
Excluded lifetime prevalence of depression at baseline[c]	189	2,382	1.31 (0.98, 1.76)
Noise cutoff L_{night} >60 dB(A)	279	3,098	1.20 (0.75, 1.93)
CES-D ≥17 only to define outcome	227	3,469	1.31 (1.00, 1.71)
Antidepressant medication only to define outcome	144	3,467	1.07 (0.74, 1.55)

[a] max. total N in model 1=3,098, numbers differing from those in table 1 reflect missing covariate data (in model 1)
[b] Adjusted for age, sex, education (not in the education-stratified analysis), income, economic activity, neighborhood-level socioeconomic status and traffic proximity (model 1); no substantial differences were in unadjusted and model 2 and 3 results (data not shown)
[c] Excluded 176 who reported having/having ever had depression and 605with missing data

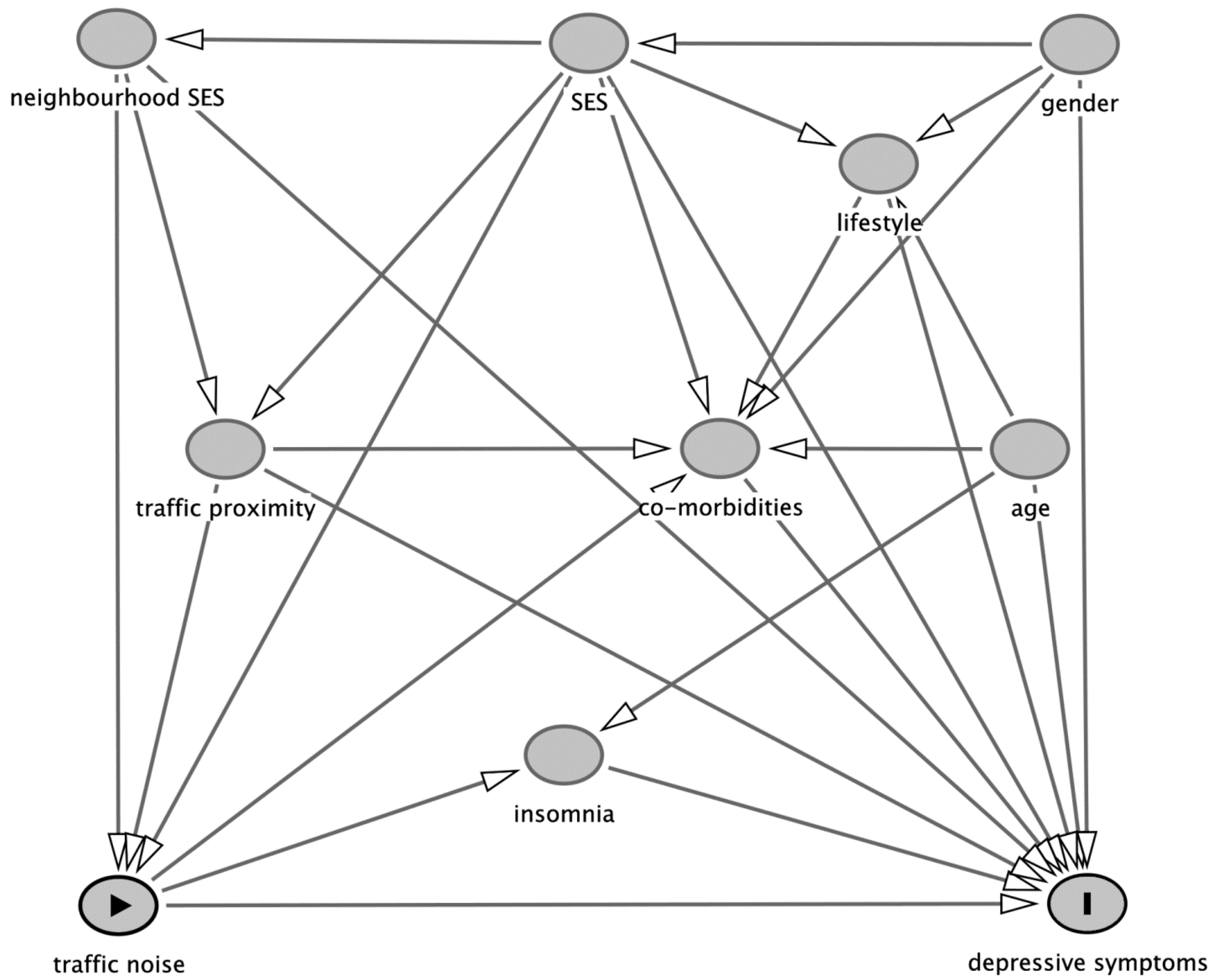

Figure S1 Directed acyclic graph (DAG) on the hypothesized associations between road traffic noise, depressive symptoms and covariates in our study. Source: Created with DAGitty (www.dagitty.net, Textor et al. 2011)

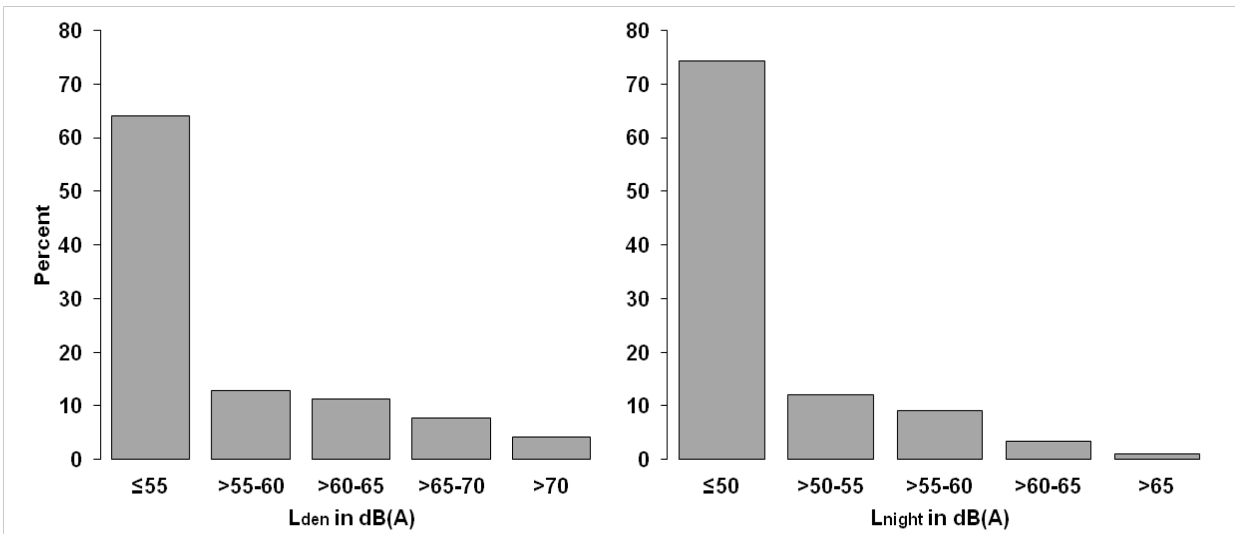

Figure S2 Distribution of Heinz Nixdorf Recall study participants (n=3,300) by residential level of annual mean 24-hour (L_{den}) and nighttime noise (L_{night}) at the residential locations.

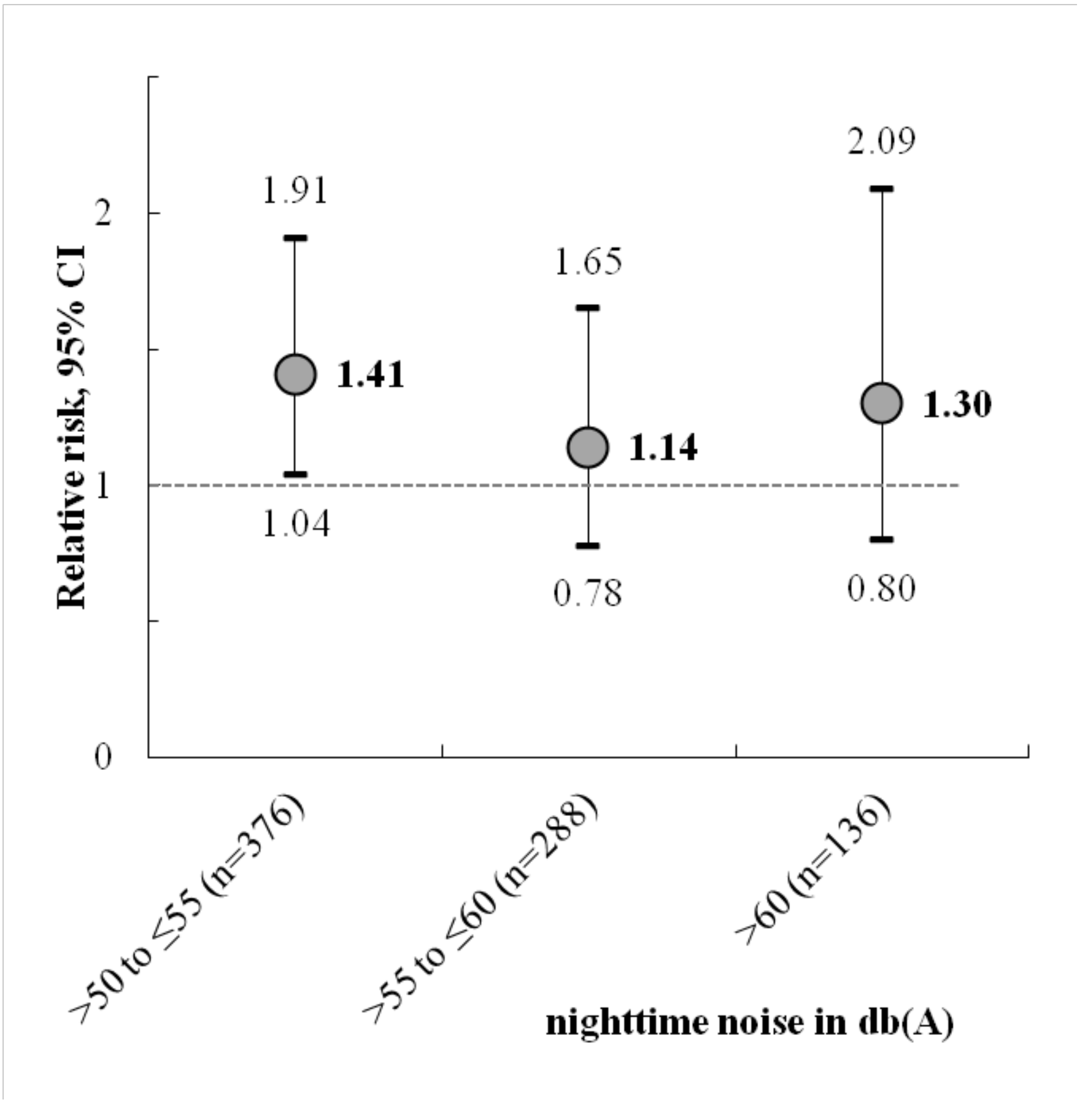

Figure S3 Relative risks and 95% confidence intervals of depressive symptoms at follow-up in association with exposure to different categories of nighttime noise compared with the lowest noise category [≤50 dB(A); n=2,298], adjusted for baseline age, sex, education, income, economic activity, neighborhood-level socioeconomic status and traffic proximity (model 1).

8.3 Paper 2: Surrounding greenness, neighborhood environment and social relations, and self-rated health

Original title: Residential surrounding greenness, self-rated health and interrelations with aspects of neighborhood environment and social relations

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Residential Surrounding Greenness, Self-Rated Health and Interrelations with Aspects of Neighborhood Environment and Social Relations

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Abstract Previous research suggests that green environments positively influence health. Several underlying mechanisms have been discussed; one of them is facilitation of social interaction. Further, greener neighborhoods may appear more aesthetic, contributing to satisfaction and well-being. Aim of this study was to analyze the association of residential surrounding greenness with self-rated health, using data from 4480 women and men aged 45–75 years that participated in the German population-based Heinz Nixdorf Recall study. We further aimed to explore the relationships of greenness and self-rated health with the neighborhood environment and social relations. Surrounding greenness was measured using the Normalized Difference Vegetation Index (NDVI) within 100 m around participants' residence. As a result, we found that with higher greenness, poor self-rated health decreased (adjusted OR 0.90, 95% CI 0.82–0.98; per 0.1 increase in NDVI), while neighborhood satisfaction (1.41, 1.23–1.61) and neighborhood social capital (1.22, 1.12–1.32) increased. Further, we observed inverse associations of neighborhood satisfaction (0.70, 0.52–0.94), perceived safety (0.36, 0.22–0.60), social satisfaction (0.43, 0.31–0.58), and neighborhood social capital (0.53, 0.44–0.64) with poor self-rated health. These results underline the importance of incorporating green elements into neighborhoods for health-promoting urban development strategies.

Keywords Surrounding greenness · Self-rated health · Neighborhood satisfaction · Social capital · NDVI

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Introduction

The built environment has been broadly recognized as a determinant of human health [1]. Differences in health status within cities partially stem from differences in environmental conditions [2]. Greenness is an environmental feature which is increasingly studied in the context of health, and green environments have been linked to better population health [3–8] and reduced mortality [9] in previous research. Unfortunately, access to green space is often not equitably distributed with regard to socioeconomic background of city residents [10].

Next to the physical environment, the neighborhood comprises a social environment characterized, e.g., by good neighborly relationships. Both physical and social aspects of the neighborhood environment and how they are perceived may influence residents' health [11]. A recent study found positive associations between trust of neighbors, exchange of help with neighbors, participation in social activities or organizations, and satisfaction with physical environments and self-rated health [12]. Considering the social environment, social relationships and networks are a valuable health resource [13–15] and represent a core aspect of the so-called social capital [16].

Attributes of neighborhoods may contribute to the health effects of social aspects [17], and it has been suggested that social cohesion may explain parts of the association of green space and health because green spaces offer opportunities to meet and connect [18]. The role of social contacts in the association between greenness and health has been investigated in a previous study [19] which found that loneliness and perceived shortage of social support partially mediated the relation between green space and health. Another study came up with the same result [20] and Sugiyama et al. similarly concluded that social coherence may contribute to the relationship between greenness and mental health, but found no empirical evidence for such an association for physical health [21].

In order to gain deeper insight into the complex relationships between the social and physical environment—and particularly surrounding greenness—and health, the aim of our study was to investigate the following:

1. The association between residential surrounding greenness and self-rated health,
2. The association between residential surrounding greenness and neighborhood environment (*neighborhood satisfaction*, *perceived safety*) and social relations (*social satisfaction*, *neighborhood social capital*), and
3. The associations of neighborhood environment (*neighborhood satisfaction*, *perceived safety*) and social relations (*social satisfaction*, *neighborhood social capital*) with self-rated health.

So far, the relationships between greenness in immediate residential surroundings and the mentioned neighborhood environment and social factors have been rarely studied, particularly in combination with self-rated health. Early observations [22] and more recent studies suggest that green and natural views (e.g., from a window) can have a positive impact on health by alleviating stress and facilitating mental restoration [22–25]. Therefore, we think it is important to study greenness in immediate residential surroundings in addition to, e.g., distance to parks and public green spaces, as the relationship with health, well-being, and satisfaction as well as with social ties may differ for different aspects of greenness.

Methods

Study Population

We analyzed data from participants of the Heinz Nixdorf Recall (HNR) study which was conducted in three adjacent cities (Bochum, Essen, and Mülheim/Ruhr) in the metropolitan Ruhr region in Germany (Fig. 1). Details of the design of the HNR have been published elsewhere [26]. In brief, study participants ($n = 4814$ women and men aged 45–75 years) were randomly selected from population registries and enrolled between 2000 and 2003. The examinations were performed in the Heinz Nixdorf Study Center, Essen, and the baseline response calculated as recruitment efficacy proportion was 55.8% [27]. The study maintained extensive quality management procedures, including a certification and re-certifications according to DIN ISO 9001:2000/2008. It was approved by the local ethics committees and all participants gave informed consent prior to participation.

Exposure Assessment

Level of surrounding greenness at each participant's residence was measured using the Normalized Difference Vegetation Index (NDVI) [28]. The NDVI is commonly used as an indicator of the presence and level of green vegetation. Values of NDVI range from −1 to +1; those approaching −1 generally correspond to water, while values around 0 represent bare surfaces with sparse vegetation, e.g., rock, rooftops, and roads, and values close to 1 represent dense green vegetation. It is calculated according to the level of reflectance of near-infrared and visible red wavelength spectra detected by satellite, using the formula [29]

$$\mathrm{NDVI} = (\text{near infrared–red})/(\text{near infrared} + \text{red})$$

We calculated NDVI across the study area at a 30-m resolution based on United States Geological Survey Landsat 5 Thematic Mapper satellite data bands 3 and

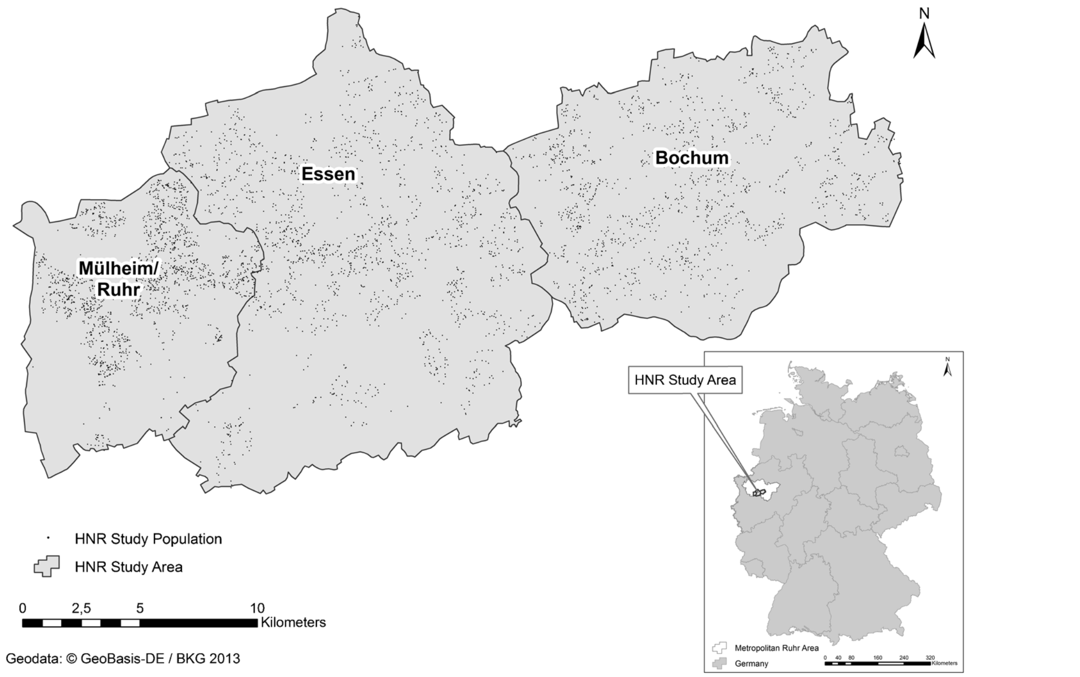

Fig. 1 Map of the location of the Heinz Nixdorf Recall (HNR) study area in Germany and the distribution of participants' residences in the cities Mülheim/Ruhr, Essen, and Bochum

4 (from 10 July 2003, a cloudless day), using the geographic information system (GIS) ArcMap 10.3.1. After excluding negative NDVI values to eliminate any confusion of water—a potentially positive environmental exposure—with poor greenness, we calculated the mean NDVI within a buffer of 100 m around the participants' addresses (see Fig. 2) using Geospatial Modeling Environment. Residential surrounding greenness measured by NDVI thus refers to the general vegetation level in this area. The 100-m buffer was chosen to represent the immediate ("next-door") neighborhood and has also been applied in previous studies using the NDVI [20, 30]. For additional analyses, we also calculated the NDVI in a buffer of 1000 m to apply a broader scale of neighborhood. We used this bigger difference to the 100-m buffer because mean NDVI in buffers of 250 and 300 m were strongly correlated with the 100-m values in our population ($r = 0.8$, $p < 0.0001$), while the 1000-m NDVI was less correlated ($r = 0.5$, $p < 0.0001$).

Self-Rated Health

Information on self-rated health was obtained in a standardized computer-assisted personal interview by the question "How would you describe your overall health status during the last twelve months?" on a five-point Likert scale ("very good," "good," "fair," "poor," or "very poor"). This health measure was dichotomized, with the answers "poor" or "very poor" representing poor self-rated health status, in order to receive a binary outcome variable for easier interpretation of logistic regression estimates. Dichotomization of the self-rated health variable has been shown to provide robust results when compared with statistical approaches based on the original categories [31].

Neighborhood Environment and Social Relations

Participants rated satisfaction with their neighborhood (note: the term neighborhood refers to the physical residential environment in this context) and social relations, as well as trust in neighbors, helpfulness of neighbors, and perceived neighborhood safety in a questionnaire.

The questions "How satisfied are you with your residential area?" (*neighborhood satisfaction*) and "How satisfied are you with your relations to friends, neighbors, acquaintances?" (*social satisfaction*) could be answered by "very unsatisfied", "rather unsatisfied," "rather satisfied", or "very satisfied". Both of these

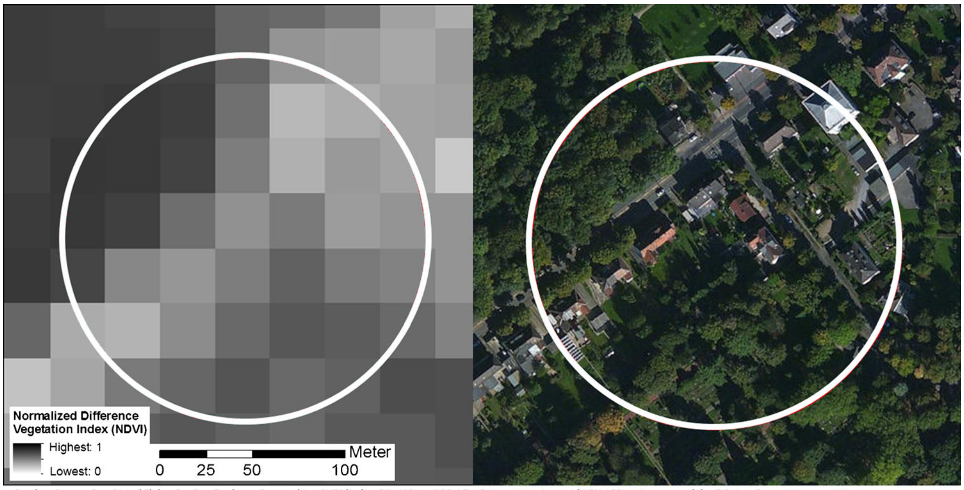

Fig. 2 Raster layer with NDVI values in 30-m resolution (*left*) and a satellite image (*right*) showing the same area in a 100-m buffer. This example shows a mean NDVI of 0.5 in the 100-m buffer

items were dichotomized with “very/rather unsatisfied” being the negative and “very/rather satisfied” the positive response.

Agreement with the statements “Most people in my neighborhood are helpful”, “I can trust most people in my neighborhood”, and “I feel safe during daytime in the area where I live” (*perceived safety*) was expressed by the options “fully disagree”, “rather disagree” “rather agree” or “fully agree.” These items were dichotomized, with “fully/rather disagree” being the negative and “fully/rather agree” the positive response. The information on trust in and helpfulness of neighbors was combined to create a dichotomous variable *neighborhood social capital*. If participants responded positively concerning both helpfulness of and trust in neighbors, *neighborhood social capital* was categorized as high. Note that this definition assesses *neighborhood social capital* on individual level. Further, the scale of neighborhood/living area is not defined in the questionnaire and thus a matter of subjective interpretation.

Covariates

Information was obtained through standardized computer-assisted personal interviews and by self-completed paper and pencil questionnaires. Education and employment status were included as indicators of individual socioeconomic position (SEP). Education was defined by combining school and vocational training as total years of formal education according to the International Standard Classification of Education [32] and categorized into four groups (≤10, 11 to 13, 14 to 17, and ≥18 years). Employment status was also divided into four groups (employed, inactive/homemaker, retired, and unemployed).

Sociodemographic and behavioral covariates including date of birth, household size, and smoking (current, former or never-smoker) were assessed via standardized computer-assisted interviews. Height and weight were obtained by standardized anthropogenic measurements during the clinical examination. The body mass index (BMI) was calculated as (weight in kg/[height in m]^2).

We applied the 2001 unemployment rate in the respective city unit/district (German terms: in Essen “Stadtteil”, in Bochum and Mülheim/Ruhr “statistischer Bezirk”) as an indicator of neighborhood-level SEP. This data was obtained from the local census authorities of the respective cities of Bochum, Essen, and Mülheim/Ruhr [33].

Statistical Analyses

Of the 4814 participants at baseline, we excluded those with missing data on self-rated health ($n = 13$), *neighborhood satisfaction* ($n = 107$), *perceived safety* ($n = 115$), *social satisfaction* ($n = 114$), *neighborhood social capital* ($n = 221$), NDVI ($n = 5$), or covariates ($n = 46$). The final analysis sample included 4480 participants (93% of initial sample).

We used a logistic regression model to analyze the associations between neighborhood greenness and self-rated health (main analysis), as well as relationships of both of these factors with *neighborhood satisfaction*, *perceived safety*, *social satisfaction*, and *neighborhood social capital*. Odds ratios for the associations with greenness were calculated for an IQR (=0.1) increase in mean NDVI, as in other studies on residential greenness and health outcomes [20, 30, 34]. To account for potential confounding factors, we adjusted for age (continuous), sex, employment status, neighborhood-level SEP (unemployment rate, continuous), household size (>1 person, yes/no), BMI (continuous), and smoking (current, former, never). The included covariates were selected beforehand based on literature and hypothesized pathways. All analyses were conducted with SAS version 9.4.

To explore potentially differential effects in different population groups, we stratified the analysis on greenness and self-rated health by (i) sex, (ii) age (<60/≥60 years), (iii) education level (≤13/>13 years of formal education), (iv) physical activity (sports/no sports), and (v) city of residence.

Results

The mean/median NDVI in 100 m around participants' residence was 0.36 (range 0.02–0.66; Q1 = 0.30, Q2 = 0.42) and 0.40 (range 0.19 to 0.60; Q1 = 0.36, Q2 = 0.43) in the 1000-m buffer. Surrounding greenness was approximately normally distributed (Fig. 3). The overall prevalence of poor self-rated health was 16.4% ($n = 735$; men 13.1%, women 19.8%). Characteristics of the study population by self-rated health status and by surrounding greenness in 100 m are shown in Table 1. Participants with poor self-rated health were more often female, unemployed, retired, and living alone. They also had lower education and were less physically active. No major differences in mean age and BMI were observed between those with poor and good self-rated health. A vast majority of the study population was satisfied with their neighborhood, felt safe in their neighborhood, was satisfied with their social relations, and reported high *neighborhood social capital*. We observed that those with lower education (≤13 years) were more likely to live within the lowest quartile of residential greenness (NDVI in 100 m ≤0.30) compared to those with higher education. The same applies to physically inactive participants, smokers, and those reporting low *neighborhood social capital* and low *neighborhood satisfaction*. There were no differences in mean age and BMI when comparing by greenness.

Residential Surrounding Greenness and Self-Rated Health

The regression analysis revealed an inverse association of higher greenness and poor self-rated health, with an adjusted OR of 0.90 (95% CI 0.82–0.98) per 0.1-increase in NDVI within the 100-m buffer. The crude OR did not differ much (Table 2). The association between greenness and self-rated health was similar in the 1000-m buffer with an adjusted OR of 0.90 (95% CI 0.77–1.05) (Table 2).

Stratified analyses indicated no differences in the association between greenness and self-rated health by gender, education, and city of residence. Comparisons by age group and physical activity revealed that the association was present only among participants younger than 60 years and those who were physically inactive (Table 3).

Residential Surrounding Greenness and Neighborhood Environment and Social Relations

An increase of 0.1 in NDVI in the 100-m buffer was positively associated with *neighborhood satisfaction* (OR 1.41, 95% CI 1.23–1.61) and *neighborhood social capital* (OR 1.22, 95% CI 1.12–1.32) in the adjusted model, but not with perceived safety (OR 1.12, 95% CI 0.86–1.44) and social satisfaction (OR 0.98, 95% CI 0.84–1.15). As shown in Table 2, the crude estimates were somewhat decreased by adjustment, particularly for *neighborhood satisfaction* (crude OR 1.59) and *perceived safety* (crude OR 1.37). Magnitude of the associations was similar considering NDVI in a 1000-m buffer. It is noticeable that the effect of adjustment on the crude estimates for *neighborhood satisfaction* (crude OR 2.05) and *perceived safety* (crude OR 1.80) was even more pronounced for the association with greenness in 1000 m around the residence.

Neighborhood Environment and Social Relations and Self-Rated Health

Results of the regression analysis showed a negative association between all investigated aspects of the neighborhood environment and social relations with poor self-rated health (Table 2). The OR for poor self-

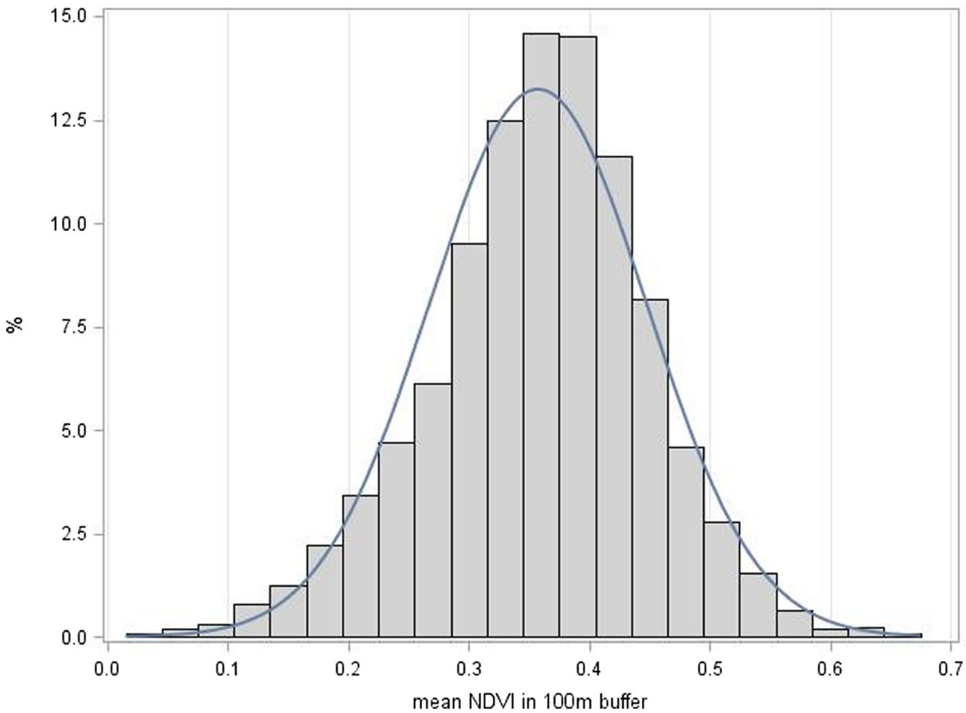

Fig. 3 Distribution of greenness (mean NDVI in a 100-m buffer) in the study population ($n = 4480$); normal density curve

rated health in the adjusted model was lowest for those reporting high perceived safety (0.36, 95% CI 0.22–0.60), followed by those with high *social satisfaction* (0.43, 95% CI 0.31–0.58), high *neighborhood social capital* (0.53; 95% CI 0.44–0.64), and high *neighborhood satisfaction* (0.70, 95% CI 0.52–0.94).

Further Results

Neighborhood satisfaction and *social satisfaction* were positively associated with *neighborhood social capital* and were also strongly associated with each other (for estimates see Supplement, Table S1a and b). *Social satisfaction* was more strongly associated with *neighborhood social capital* than *neighborhood satisfaction*, while *neighborhood satisfaction* showed a more pronounced association with *perceived safety*, which was not significantly associated with *social satisfaction*.

Discussion

In the present study, we found that a 0.1-increase in residential NDVI reduced the odds of poor self-rated health by approximately 10%, considering both the 100- and 1000-m scale and taking into account potential confounders. Further, residential greenness was positively associated with *neighborhood satisfaction* and *neighborhood social capital* which in turn were also associated with less poor self-rated health. *Social satisfaction* and *perceived safety* were associated with better health, but not with greenness.

Our results are in line with previous studies, where greenness has shown associations with different health aspects and outcomes [6, 35]. When comparing our results to those of other studies, it is important to bear in mind that a variety of different methods has been used to assess “greenness” in this research field [36]. These include subjective perception of greenness [21] or self-reports of visiting green space [37], access to public green spaces such as parks as well as objective measures of surrounding greenness at residence, such as the NDVI applied in our study. Nevertheless, other studies that used objective measures of greenness as exposure variable and self-rated health as an outcome show results that point in the same direction as ours [20, 38, 39].

A connection between greenness and health seems intuitively plausible, but the mechanisms are not yet fully understood. For example, proximity to green spaces such as parks may encourage physical activity

Table 1 Characteristics of the study population by self-rated health status and by level of surrounding greenness ($n = 4480$)

	Good health		Poor health		High 100-m NDVI (>0.30)		Low 100-m NDVI (≤0.30)		Total	
	N	%	*N*	%	*N*	%	*N*	%	*N*	%
Total	3745	83.6	735	16.4	3415	76.2	1065	23.8	4480	100.0
Female	1786	47.7	440	59.9	1675	49.0	551	51.7	2226	49.7
Education										
≤10 years	346	9.2	119	16.2	334	9.8	131	12.3	465	10.4
11–13 years	2081	55.6	420	57.1	1872	54.9	629	58.9	2501	55.8
14–17 years	870	23.2	148	20.1	800	23.4	218	20.4	1018	22.7
≥18 years	448	12.0	48	6.5	408	11.9	88	8.3	496	11.1
Employment status										
Employed	1627	43.4	221	30.1	1393	40.8	458	42.7	1848	41.3
Inactive/homemaker	475	12.7	123	16.7	460	13.5	138	13.0	598	13.3
Retired	1430	38.2	317	43.1	1355	39.7	392	36.8	1747	39.0
Unemployed	213	5.7	74	10.1	207	6.1	80	7.5	287	6.4
Household size >1 person	3177	84.8	563	76.6	2911	85.2	829	77.8	3740	83.5
No sports	1611	43.0	428	58.2	1507	44.1	532	50.0	2039	45.5
Smoking										
Non-smoker	1566	41.8	311	42.3	1448	42.4	429	40.3	1877	41.9
Former smoker	1330	35.5	238	32.4	1216	35.6	352	33.1	1568	35.0
Current smoker	849	22.7	186	25.3	751	22.0	284	26.7	1035	23.1
Neighborhood satisfaction (satisfied)	3532	94.3	670	91.2	3241	94.9	961	90.2	4202	93.8
Perceived safety (feel safe)	3701	98.8	708	96.3	3368	98.6	1041	97.7	4409	98.4
Social satisfaction (satisfied)	3598	96.1	671	91.3	3251	95.2	1018	95.6	4269	95.3
Neighborhood social capital (high)	3103	82.9	524	71.3	2823	82.7	804	75.5	3627	81.0
NDVI (100 m) ≤0.30	860	23.0	205	27.9	–	–	–	–	1065	23.8
City of residence										
Mülheim/Ruhr	1401	37.4	253	34.4	1263	37.0	391	36.7	1654	36.9
Bochum	1107	29.6	202	27.5	1073	31.4	236	22.2	1309	29.2
Essen	1237	33.0	280	38.1	1079	31.6	438	41.1	1517	33.9
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age	59.4	7.7	60.0	7.9	59.5	7.7	59.4	8.0	59.5	7.8
Body mass index	27.7	4.4	28.6	5.4	27.8	4.5	28.2	4.9	27.9	4.6
NDVI 100-m buffer	0.36	0.09	0.35	0.09	0.40	0.06	0.24	0.05	0.36	0.09
NDVI 1000-m buffer	0.40	0.06	0.39	0.06	0.41	0.05	0.35	0.06	0.40	0.06
% unemployed in district	12.4	3.4	12.9	3.6	12.1	3.3	13.9	3.6	12.5	3.4

and thus promote health. However, our aim was to investigate the impact of residential surrounding greenness using the NDVI, so the access to green recreational areas was not measured in our study. We found an association between greenness and health only in the physically inactive, and those with lower surrounding greenness were less physically active in our study, which may imply higher health benefits from physical activity than from greenness. A review of studies comparing physical and mental well-being benefits of indoor vs. outdoor physical activity found some support favoring activity in natural outdoor environments, but the authors caution that further research is needed in this area [40]. Yet, in our study we had no information on

Table 2 Odds ratios with 95% confidence intervals for the associations between surrounding greenness, neighborhood environment and social relations, and self-rated health ($n = 4480$)

	Poor self-rated health	Neighborhood satisfaction (satisfied)	Perceived safety (feel safe)	Social satisfaction (satisfied)	Neighborhood social capital (high)
NDVI 100 m[a]					
Unadjusted	0.85 (0.78, 0.93)	1.59 (1.40, 1.81)	1.37 (1.06, 1.75)	1.11 (0.95, 1.29)	1.32 (1.21, 1.43)
Adjusted[b]	0.90 (0.82, 0.98)	1.41 (1.23, 1.61)	1.12 (0.86, 1.44)	0.98 (0.84, 1.15)	1.22 (1.12, 1.32)
NDVI 1000 m[a]					
Unadjusted	0.77 (0.68, 0.88)	2.05 (1.68, 2.49)	1.80 (1.23, 2.62)	1.31 (1.04, 1.63)	1.55 (1.37, 1.76)
Adjusted[b]	0.90 (0.77, 1.05)	1.54 (1.23, 1.94)	1.08 (0.70, 1.68)	1.09 (0.84, 1.42)	1.36 (1.18, 1.57)
Poor self-rated health (=dependent variable)					
Unadjusted	–	0.62 (0.47, 0.83)	0.31 (0.19, 0.51)	0.43 (0.32, 0.58)	0.51 (0.43, 0.62)
Adjusted[b]	–	0.70 (0.52, 0.94)	0.36 (0.22, 0.60)	0.43 (0.31, 0.58)	0.53 (0.44, 0.64)

[a] OR per 0.1 NDVI increase

[b] Adjusted for age, sex, employment status, neighborhood-level SEP, household size, BMI, and smoking

whether physical activity was performed outdoors. Based on what is known from previous research and our study results, we assume that green surroundings positively influence health, well-being, and satisfaction. This would be in line with the so-called biophilia hypothesis introduced by Edward O. Wilson [41]. It describes an innate affinity towards nature and other living beings which is, as a result of evolution, deeply rooted in the human biology. Thus, humans would be born with a preference for natural elements and surroundings, and consequently, a lack of these may impair their well-being. The biophilia hypothesis finds support in a large variety of publications including experimental and observational research on stress recovery, visual and restorative effects of nature and green, physical activity in natural environments, and diverse aspects of human health and well-being [42, 43].

Our result of increased *neighborhood satisfaction* in the presence of higher surrounding greenness further confirms a preference of green environments and stresses the necessity of incorporating natural elements in the design of urban living areas. This association has been observed in previous studies as well. For example, Hur et al. [44]. found correlations of both objective greenness (NDVI) and perceived naturalness and openness with overall neighborhood satisfaction in a sample of 725 homeowners in Franklin County, Ohio. Similarly, a Swedish study of 24,847 public health survey participants found associations of perceived green qualities with neighborhood satisfaction, physical activity, and general health which were mostly confirmed for GIS-assessed green qualities [45]. Another study [46] found associations with various aspects of GIS-measured landscape structure, such as variety in size and shape of tree patches, and neighborhood satisfaction in a mailed survey including 311 single-family households in the city of College Station, Texas. Results like these were also found in an analysis of the LARES survey [7]. Overall, it is not fully clear how greenness and nature add to neighborhood satisfaction, especially if it does more than increasing the neighborhood's attractiveness.

We observed an association of surrounding greenness with *neighborhood social capital*, but not with *social satisfaction* and *perceived safety*. This may be because *social satisfaction* is influenced by various factors that may outweigh the impact of greenness. Also, this variable may depend more on social relationships that exist outside the neighborhood, as opposed to the *neighborhood social capital* (e.g., friends/family vs. neighbors). Participants more frequently reported *social satisfaction* than high *neighborhood social capital*. It is striking that *social satisfaction* did not differ by greenness, while *neighborhood social capital* showed big differences by both greenness and self-rated health status (Table 1). One possible explanation for this finding is that participants with lower greenness may be likelier to live in deprived neighborhoods. Previous studies [47, 48] have found that living in deprived neighborhoods was associated with lower social capital (in terms of trusting neighbors, helping each other out, etc.), which may add to the observed result in our study. Considering *perceived safety*, total number of participants who did not feel safe was very

Table 3 Odds ratios with 95% confidence intervals for the association between a 0.1 increase in NDVI (100 m) and poor self-rated health in different population strata

	Cases (*N*)	Total (*N*)	Unadjusted OR (95% CI)	Adjusted OR (95% CI)[a]
Sex				
Male	295	2254	0.84 (0.74, 0.97)	0.91 (0.79, 1.06)
Female	440	2226	0.86 (0.77, 0.96)	0.89 (0.79, 1.00)
Age				
<60 years	382	2388	0.77 (0.69, 0.87)	0.84 (0.74, 0.95)
≥60 years	353	2092	0.96 (0.84, 1.09)	0.97 (0.85, 1.11)
Education				
≤13 years	539	2966	0.87 (0.79, 0.96)	0.91 (0.82, 1.01)
>13 years	196	1514	0.86 (0.72, 1.01)	0.88 (0.74, 1.05)
Sports				
Yes	307	2441	0.94 (0.82,1.08)	1.01 (0.88, 1.16)
No	428	2039	0.82 (0.73, 0.92)	0.83 (0.73, 0.93)
City of residence				
Mülheim/Ruhr	253	1654	0.88 (0.75, 1.03)	0.91 (0.76, 1.09)
Bochum	202	1309	0.86 (0.72, 1.02)	0.88 (0.73, 1.05)
Essen	280	1517	0.85 (0.75, 0.97)	0.91 (0.79, 1.04)

[a] Adjusted for age (not in age-strata), sex (not in sex-strata), employment status, neighborhood-level SEP, household size, BMI, and smoking

limited ($n = 71$) and thus confidence intervals were rather broad for the greenness-safety relationship. The odds ratio showed a tendency towards a positive effect of higher greenness on *perceived safety*, though, and safety was also related to *neighborhood satisfaction*. One advantage of our study is that we had the opportunity to study both *social satisfaction* in general and *social capital* specifically relating to neighbors. Social relations have been investigated in the context of greenness and health before, and some studies support the hypothesis of potential mediation in this context [19, 20, 49]. In contrast, Fan et al. [50] found a negative effect of neighborhood greenness on social support. An earlier study found an association between the use of green outdoor common spaces and social ties and sense of community in a sample of 91 elderly inner city inhabitants [51]. It is possible that both greenness and relations with neighbors influence the perception of the neighborhood (satisfaction). Though the question "How satisfied are you with your residential area?" intends to capture satisfaction with the physical environment, answers to it may not only reflect the respondent's attitude towards physical aspects but also the perception of the people sharing the neighborhood, depending on the interpretation of the question.

Regarding the association between *neighborhood satisfaction* and self-rated health found in our study, our results also support previous research. A Japanese study ($n = 8139$) observed an association of neighborhood dissatisfaction with poor self-rated health with an OR of 1.22 (95% CI 1.04–1.42), adjusting for various contextual and individual factors, including personality traits and sense of coherence [52]. Another study analyzed data of 199,790 participants of the Korean Community Health Survey [12]. This study used similar questionnaire instruments as the HNR study and found that trust of neighbors, exchange of help with neighbors, frequent contact with friends/neighbors, and satisfaction with the physical environment, including perceived safety, were positively associated with self-rated health in both urban and rural communities, after adjusting for relevant confounding factors. Similar results were reported based on findings from a computer-assisted telephone survey carried out in Vancouver which also found that neighborhood dissatisfaction was associated with fair/poor self-reported health (OR 2.24, 95% CI 1.65–3.03) [53]. It is tempting to suggest that satisfaction increases health, which has also been found in a previous prospective study on life satisfaction and health [54]. However, it is not possible to infer the direction of this association from our cross-sectional design. Those who report better health may generally be more satisfied with other aspects of their life, including their neighborhood and social relations. For instance, *neighborhood satisfaction* and *social satisfaction* were strongly associated (supplement, Table S1). Also, information about perception of the neighborhood and social environment as well as individual health was obtained from self-reports by the same individuals, which may introduce same-source bias [55].

General strengths of this study include an objective measure of greenness based on high-quality satellite imagery and individual exposure assessment based on residential addresses. The outcome self-rated health was assessed by a widely used and simple instrument which has been shown to well-reflect objective health status [56]. We investigated a large number of randomly selected participants, allowing associations to be studied in different subgroups. Furthermore, comprehensive measurements enabled inclusion of many potential confounding factors in our analyses. We had only few dropouts due to missing data (7% of the initial cohort), which makes bias due to missing data unlikely.

Regarding limitations of our study apart from already mentioned ones, the exposure assessment has some drawbacks. While the NDVI is considered a good tool for quantifying neighborhood greenness [28], it does not provide information about the present type, or "quality," of greenness. It is not possible to distinguish trees from grass or bushes using the NDVI, for example. Future research would thus profit from additionally incorporating measures of type or quality of greenness. This is important for city planners, as there may be specific types of greenness that are particularly valuable for health [57]. Also, we had no information about actual use of the greenness, non-residential exposures to greenness such as park visits, or time spent in other environments, including the workplace. This may contribute to exposure misclassification. Further, causal inference is not possible based on the cross-sectional study design. We investigated a general population sample of middle-aged and older men and women living in an urbanized area in Germany and hence our results cannot be generalized to populations from other countries, or children, young adults, and residents of very rural areas. While most previous studies on health effects of green environments have focused on adult populations, several studies support associations of greenness with different health indicators in children as well [58–60].

Conclusion

According to our results, there is an association between residential surrounding greenness and self-rated health. This result adds to existing evidence suggesting that greenness is a beneficial health resource. Further, higher greenness was associated with *neighborhood satisfaction* and *neighborhood social capital*, which were also associated with better self-rated health. Incorporating green elements even in small-scale neighborhoods may represent an important mean of improving city dwellers' health and well-being, possibly also by positively influencing social capital. In this context, the importance of creating environmental equality cannot be stressed enough, especially as we—like other authors before—found an unequal distribution of greenness by socioeconomic position. Since various different methods are used to study green environments, improving understanding of what these different indicators of greenness measure and how they can be evaluated and combined in health research are crucial tasks for further research.

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Supplemental material to "Residential Surrounding Greenness, Self-Rated Health and Interrelations with Aspects of Neighborhood Environment and Social Relations"

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Table S1 Relationships between neighborhood environment and social relations

a) Associations with **neighborhood satisfaction**	
	OR (95% CI)
Perceived safety	3.77 (2.07, 6.86)
Social satisfaction	8.92 (6.39, 12.45)
Neighborhood social capital	2.41(1.83, 3.19)
b) Associations with **social satisfaction**	
	OR (95% CI)
Neighborhood satisfaction	8.89 (6.37, 12.40)
Perceived safety	1.42 (0.71, 2.84)
Neighborhood social capital	4.75 (3.51, 6.42

Curriculum vitae

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.