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CESifo Working Paper No. 6281
Category 5: Economics of Education
December 2016

ISSN 2364-1428

CESifo
Center for Economic Studies & Ifo Institute

CESifo *Working Paper No. 6281*

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Abstract

Noise pollution is detrimental to health and to cognitive development of children. This is not only true for extreme levels of noise in the neighborhood of an airport but also to traffic noise in urban areas. Using a census of preschool children, we show that children who are exposed to intensive traffic noise significantly fall behind in terms of school readiness. Being exposed to additional 10 dB(A) compares to about 3 months in kindergarten. We contribute to the literature and the policy debate by working with administrative data and focusing on everyday exposure to noise. The proposed method is easily applied to other regions. We assess the public costs of different abatement instruments and compare the costs to the benefits. It turns out that the commonly used abatement measures like quiet pavement or noise protection walls in densely populated areas of about 3,000 to 5,000 inhabitants per km2 can be cost efficient, even with a conservative assessment of the benefits.

JEL-Codes: I180, I260, Q530, H230, H540.

Keywords: noise, child development, early education, abatement, abatement costs.

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December 2016

1. Introduction

Children are exposed to noise throughout the day and also at night. In kindergarten, for example, the noise level produced by children themselves may even exceed 120 dB(A)[1], which corresponds to a jet take-off in 160 meters distance. And if the kindergarten is located at a busy street, children are exposed to a sound level of about 90 dB(A). This is louder than a hairdryer and might cause severe and chronic hearing damage (Tamburlini 2002, p. 32). Back at home, TV noise, background music, the vacuum cleaner and toys produce intrusive or annoying sounds. A rubber duck causes the same sound pressure level as a diesel truck; but, off course, no one is exposed to the sound of a rubber duck 24 hours a day. More importantly, exposure to aircraft and traffic noise has become one of the biggest problems of industrial countries and especially urban regions (WHO 2011).

The effect of environmental pollution on child development has been on the research agenda with a focus on air pollution (for a survey cf. Currie et al. 2014) and in particular air pollution from motor vehicle emissions on infant health (examples are Currie/Walker 2011, Coneus/Spiess 2012, Knittel/Miller/Sanders 2016). The effects of noise are less prominent in the economic literature, but have been studied in many ways. Impairment of early childhood development caused by noise may have lifelong effects on academic achievement and health. Especially indirect adverse effects of persistent noise on children's health and development are fairly well understood. There is evidence for negative effects on child's health through different channels, e.g. blood pressure, stress hormones, sleep quality or mental health (Babisch 2003, Rosenberg 1991, Cohen et al. 1980, Babisch et al. 2009, Öhrström et al. 2006, Lercher et al. 2002) and cognitive development. Already in 1973 Cohen/Glass/Singer published a study on the effects of expressway traffic on child's auditory discrimination and reading ability. The study looked at children from middle-income families living in the same

[1] dB(A) is a measure of sound level in decibels A-weighted. This approximates the sensitivity of the human ear. (Clark et al. 2006)

apartment building but on different floors. All children were enrolled in a neighborhood elementary school. The noise level was measured outside and inside the apartments. It turned out that children living on the lower floors showed an impairment of auditory discrimination. The effect persists even after controlling for background characteristics like fathers and mothers education and years of exposure (length of residence). In addition, Cohen/Glass/Singer (1973) show that impaired auditory discrimination has a significant negative effect on reading ability, i.e., vocabulary and reading comprehension. Hence, auditory discrimination mediates the adverse effect of noise on cognitive ability. Hygge/Evans/Bullinger (2002) used a natural experiment to provide evidence for the link between noise and cognitive performance of school children. In 1992 the airport München-Riem in Bavaria, Germany was closed and the new 'Franz Josef Strauß' airport was opened. The study started six months prior to the closure/opening and ended two years afterwards. During that period, the health of children of the same age and with similar socioeconomic status was monitored. Besides that, cognitive tests were performed. After the opening of the new airport, children living nearby showed an impairment of long-term memory and reading ability. At the same time, short-term memory of the group of children living close to the old and closed airport improved. Results of the RANCH[2]-project for the Netherlands, the UK and Spain are similar (Clark et al. 2006, Stansfeld et al. 2005). The negative relationship between reading comprehension and aircraft or road traffic noise is significant. Although none of these studies claims causal effects, there is sufficiently strong evidence for an existing link between noise, health and academic achievement.

While the focus in the literature and the media is more on extreme levels of noise, like noise emissions from commercial or military aircrafts, the majority of the population in industrialized countries is not exposed to extreme noise but to more moderate but permanent and

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[2] RANCH is the abbreviation for „Road traffic and Aircraft Noise Exposure and Children's Cognition and Health".

nevertheless substantial noise from road and railroad traffic. Estimates show that 42 million people in Europe[3] are affected by road noise of at least 55 dB(A) in agglomerations during the day (29.6 million with at least 50 dB(A) at night) and 28.1 (17.7) million outside agglomerations. This compares to 1.7 million people (0.64 million) affected by noise related to commercial aircrafts and 0.32 million people who are affected by industrial noise (Houthuijs et al. 2014). Knowing that noise adversely affects regeneration at night, it is in particular noise from road traffic at night that ought to be focused on. Moreover, from a public policy perspective road traffic is relevant as significant public funds are already being spent on noise protection. For instance, in 2012 Germany spent 223.1 million Euros on noise protection and renovation at federal freeways (Autobahnen) and federal highways (Bundesstrassen). Between 1978 and 2014 the total costs amount to 5,344.6 million Euros which was on average 3.5% of total expenditure for road construction (BMVI 2015). The government of North-Rhine Westphalia (NRW), the most populated German federal state, estimates that ¾ of the noise affected population suffers from noise from inner city traffic. The municipalities in NRW need an estimated 500 million Euros to finance the necessary noise protection measures.[4]

The aim of the present study is to evaluate the link between noise and cognitive development of children in more detail and to provide additional evidence, in particular for a causal interpretation of noise effects. Our study adds to the literature by showing evidence for a census of preschool children in Wuppertal, a large German city in a densely populated area of NRW. The approach has three advantages: First, we use administrative data on compulsory school readiness assessment and on noise pollution. Hence, we can study the population of preschool children and noise pollution in a region. A second advantage for policy recommendations derived from the analysis is that it can be applied to other regions as well because

[3] EEA33 (EU28 plus Iceland, Liechtenstein, Norway, Switzerland and Turkey).

[4] https://www.umwelt.nrw.de/pressebereich/detail/news/2015-03-03-landeskabinett-beschliesst-umfangreiche-laermminderungsstrategie/

these administrative data sources are available in all German municipalities. Third, we do not focus on extremely high levels of noise, like airport noise, but the everyday exposition of children to traffic noise in urban areas.

In our analysis, the estimated adverse effect of one additional dB(A) on school readiness can be compensated by about 0.36 additional months in kindergarten. Moreover, we propose the idea of a cost-benefit analysis comparing different means of noise protection.

The paper proceeds as follows: Section 2 describes the administrative data and the way school readiness and traffic noise is measured. In Section 3 we discuss our empirical strategy and Section 4 summarizes the results. Since noise protection is costly, we provide some preliminary cost-benefit analysis for different noise protection/abatement measures, based on adverse effects of noise on preschool children, in Section 5. Section 6 closes with some thoughts on the value of the study and potential extensions of the analysis.

2. Data and key measures

To estimate the effect of traffic noise on cognitive ability before school entry we combine information from three administrative sources: first, individual level information on cognitive ability before school entry; second, noise maps, i.e. raster data on noise in the city of Wuppertal caused by road traffic, railway traffic and the suspension railway (Schwebebahn), and third, residential city block information covering information on the population's socioeconomic status. Data on individuals is drawn from the *Schuleingangsuntersuchung* (school entrance medical examination), a compulsory standardized school readiness assessment that provides information on abilities, kindergarten enrollment and background characteristics like age, gender, and ethnic origin. The noise data on road traffic and the suspension railway as well as the city block information is provided by the city of Wuppertal, the department for environmental protection and the department of statistics. Data on railroad noise is provided by the German Federal Railway Authority. The different data sources are described in more detail in the following sections.

2.1. School entrance medical examination

The school entrance medical examination (SEnMed) is a compulsory and standardized examination of preschool children at the average age of 5 years and 11 months. The SEnMed is a census of all children about to enter primary school. It is conducted to assess the previous and current health status as well as cognitive and non-cognitive development of preschoolers in order to attest school readiness. The data includes information on birth weight, obesity, health conditions, social and emotional development plus several dimensions of cognitive and non-cognitive abilities. In addition, other individual characteristics like age, gender, and ethnic origin are recorded, along with the information on kindergarten and the child's prospective primary school.

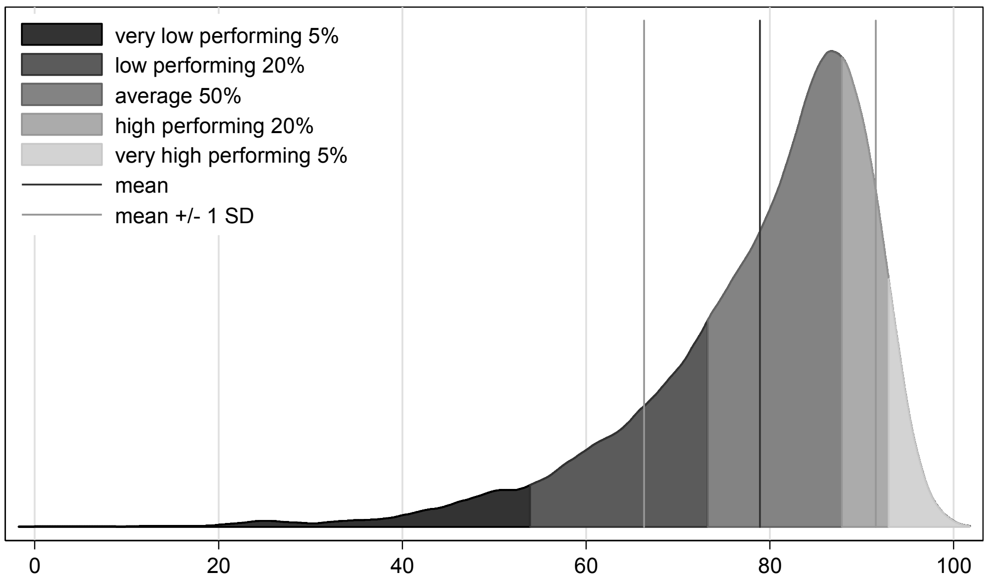
In our analysis we use data of 5,561 preschool children from two examination cohorts born between 2006 and 2008 who took the SEnMed between 2012 and 2014.[5] The children's abilities were assessed using state-wide standardized tests.[6] Theoretically, the lowest possible score is zero (no task completed) and the maximum depends on the number of tasks within a test area. There are nine test areas corresponding to different ability dimensions such as visual and analytical skills, numerical and quantitative skills, language skills, speech, and fine and gross motor skills. Typical tests include retracing of figures, visual discrimination, counting, estimating and comparing quantities, neglect tests to assess visual and selective attention, using prepositions, plural forming and repeating made-up words. Gross motor ability is assessed by asking children to jump on one leg or to walk on a straight line.

[5] 75 disabled children were excluded from the analysis because their cognitive test results are not comparable to the results of non-disabled children. 308 children not born in Germany were also excluded because it is unknown, when they migrated to Germany.

[6] The tests are confidential and neither the tests nor the (aggregate) test results are published.

Based on the test results and the child's health status, physicians and school principals decide whether a child should be enrolled in primary school or held back for a year. Note that the results of all tests, the child's health and the child's behavior during the exam jointly determine the decision on a child's school readiness. There exists no general threshold for satisfactory school readiness. Hence, for the physicians and the school principals, the overall test results are a one-dimensional latent scale of school readiness. Following this idea, we reduce the nine ability dimensions to a one-dimensional scale of school readiness. The scale is generated by an exploratory factor analysis in which we predict a school readiness index using the regression method. The results of the factor analysis confirm the conjecture of a one-dimensional factor, with 98.9% of the variance in the ability items explained by the first factor.[7] Therefore, we use the factor of school readiness as our outcome variable. To better interpret the estimation results, we transform the factor to a scale between 0 and 100. The highest value of school readiness (100%) corresponds to a score of 130 successfully completed tasks. The distribution of school readiness is shown in Figure 1.

Figure 1 School readiness, density and performance bands



Notes: average school readiness: $\bar{y} = 78.93$, $s_y = 12.60$; percentiles: $y_{0.01} = 36.75$, $y_{0.05} = 53.91$, $y_{0.25} = 73.22$, $y_{0.50} = 82.27$, $y_{0.75} = 87.84$, $y_{0.95} = 92.92$, $y_{0.99} = 95.63$.
Data source: City of Wuppertal, health department, 2015

[7] The overall KMO criterion is 0.8246; item KMO criteria lie between 0.7144 and 0.9098.

The performance bands in Figure 1 characterize five groups: the very low performing 5%, low performing 20%, average 50%, high performing 20%, and the very high performing 5%. Average school readiness is 78.9% (SD = 12.6%) and the variable is left-skewed. The weakest 5% achieve only 54% school readiness, the medium 50% achieve 73%-88% school readiness.

In addition to information on abilities, there is a large set of background variables in the SEnMed data. Table 1 summarizes the data. The sample comprises 5,561 children, 50.84% of whom are boys; 34.20% of the children are immigrants where migration status is defined by the language spoken with the child during the first four years. If parents report a language other than German, the child is said to have a migration background.

On average, the children have attended kindergarten for 2.82 years (about 2 years and 10 months) before taking the exam. About 45% have one sibling; 3.81% have four or more siblings. The share of overweight or obese children is larger than the share of (severely) underweight children. About 79% of the children have a healthy weight. 6.64% of the children have a low birth weight. The table also shows the percentage of children with health problems. For instance, 5.22% of the children are reported to suffer from a disease of the respiratory system and 24.26 % have a reduced visual acuity.

Table 1 Descriptive statistics of individual level data

Full sample size		5,561
Average age at examination		5.87 (0.1642)
% boys		50.84
% with migration background		34.20
% mother born in Germany		60.50
% father born in Germany		58.40
% children in kindergarten (at least 12 months)		92.57
Average time in kindergarten (in years)		2.82 (0.7621)
Average age at kindergarten entry (in months)		36.62 (9.1655)
Number of siblings in %	0	22.10
	1	45.10
	2	21.18
	3	7.80
	4 or more	3.81
BMI category in %	severely underweight	2.44
	underweight	5.11
	normal (healthy weight)	79.25
	overweight	7.18
	obese	6.02
Average birth weight (in gram)		3,335.77 (563.8607)
% low birth weight (below 2,500 gram)		6.64
% no health certificate presented		7.05
% with U7a (medical screening at age 34-36 months)		90.31
% with U8 (medical screening at age 46-48 months)		88.95
% with all medical screenings since birth		75.62
% no immunization record presented		8.79
% with tetanus vaccination		90.92
% with allergic rhinitis		1.19
% with bronchitis		3.35
% with asthma		1.49
% with any disease of the respiratory system		5.22
% with reduced visual acuity		24.26
% with partial hearing loss		7.68
% with behavioral problems		6.28

Note: Standard deviation in parentheses

Data source: City of Wuppertal, health department, 2015; own calculations

2.2. Noise pollution

The data on noise pollution is provided by the department for environmental protection of the city of Wuppertal and the Federal Railway Authority (*Eisenbahn-Bundesamt*). In the federal state of North-Rhine Westphalia, the municipalities are legally obligated to collect data on noise exposure. Guidelines and requirements are specified by the Ministry for Climate Protection, Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (MKULNV, *Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz* des Landes Nordrhein-Westfalen) and are, therefore, standardized and comparable. The reason for collecting the data is to measure the extent of noise pollution and to develop state-wide concepts for noise reduction and noise protection. Common structural measures for noise protection are soundproof walls, banks, tunnels or porous asphalt, the so-called quiet pavement, which absorbs sound better than regular asphalt. Between 2005 and 2014 the federal state of NRW invested about 506.1 Million Euros for noise protection and reconstruction at federal freeways (Autobahnen) (BMVI 2015). In addition, there exist strict thresholds for tolerable noise exposure for new or extended freeways and after reconstruction works. Noise levels at new or extended freeways must not exceed 49 dB(A) in residential zones at night and 57 dB(A) after reconstruction (BMVI 2015). In comparison, the noise level of a standard conversation is 50 dB(A).

According to the guidelines of the MKULNV, the municipalities compute the extent of ambient noise depending on its source (freeway (Autobahn), highway (Bundesstraße), inner city road, railway, airport, industrial site, etc.) and the usage (e.g. traffic volume, maximum speed, type of asphalt, etc.). In addition, information on noise reducing or noise increasing factors as well as noise abatement is taken into account, e.g. the topography, or whether the road passes natural barriers or high buildings or the distance to soundproof walls.

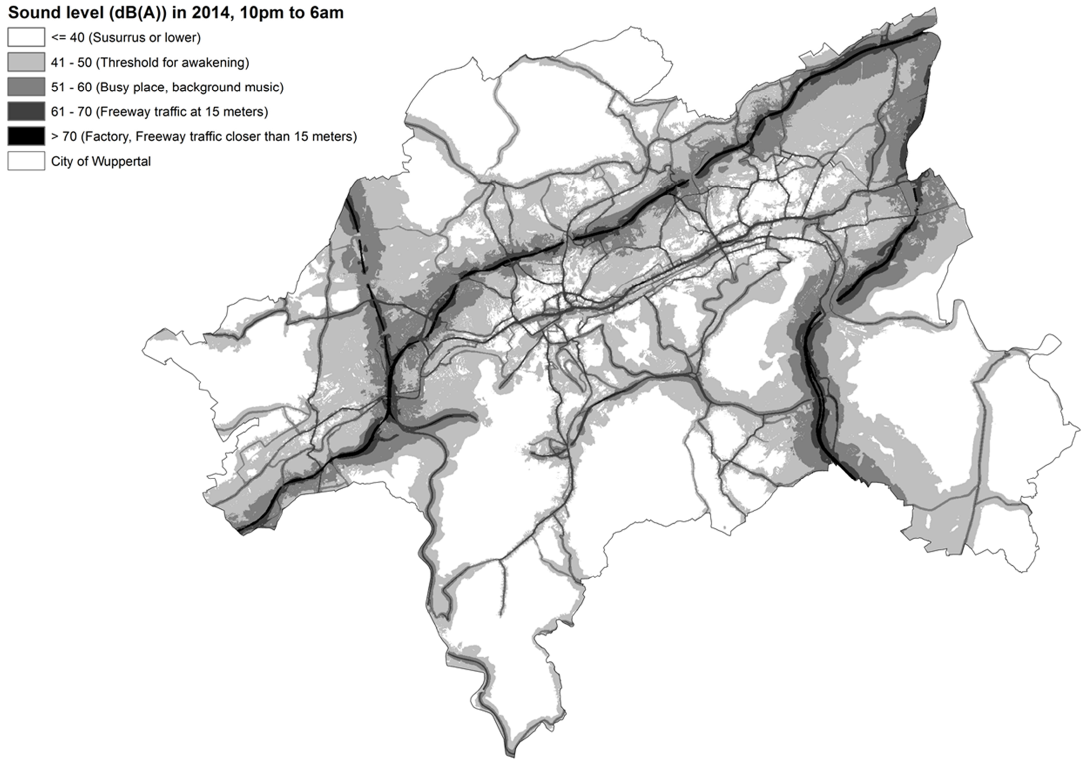
The information on ambient noise is available for 2014 and comprises information on noise during the day (6am to 10pm) and at night (10pm to 6am) collected between 2011 and

2014. Moreover, the data distinguishes noise from roads, from Wuppertal's suspension railway (Schwebebahn) and from the German Federal Railway. As noted earlier, in our analysis we focus on the data available on noise at night. Of course, the noise level is lower at night but it is even more likely to have a significant effect on health and cognitive development, as it impairs the quality of sleep and regeneration (WHO 2009). This is in particular true for children and elderly people. Moreover, children spend most of their time in the evening and at night at home. Here, a noise level exceeding susurrus (about 40 dB(A)) is sufficient to wake someone up (WHO 2009, p. XIII) and thus to cause disordered sleep.

Also due to its topography, traffic noise is of major concern in Wuppertal (see Figure 2 and 3) in particular at the so called 'Talachse' (valley axis) ranging from northeast to southwest. The city of Wuppertal is divided by one of the high-traffic freeways in NRW, the A46 (Figure 3, red), which connects the Rhine area (Düsseldorf, Köln) with the Ruhr area (Dortmund, Bochum, Essen). In the northeast of the city, the A46 connects with the A1 and A43, which are another important freeways linking the Ruhr metropolitan region to Köln. In the southwest, the A46 leads to the A535. In addition, the A46 is also considered a city freeway, which means that it is not only used for long distance traffic. On average 71,600 vehicles per day use the freeway passing through Wuppertal (BASt 2011).

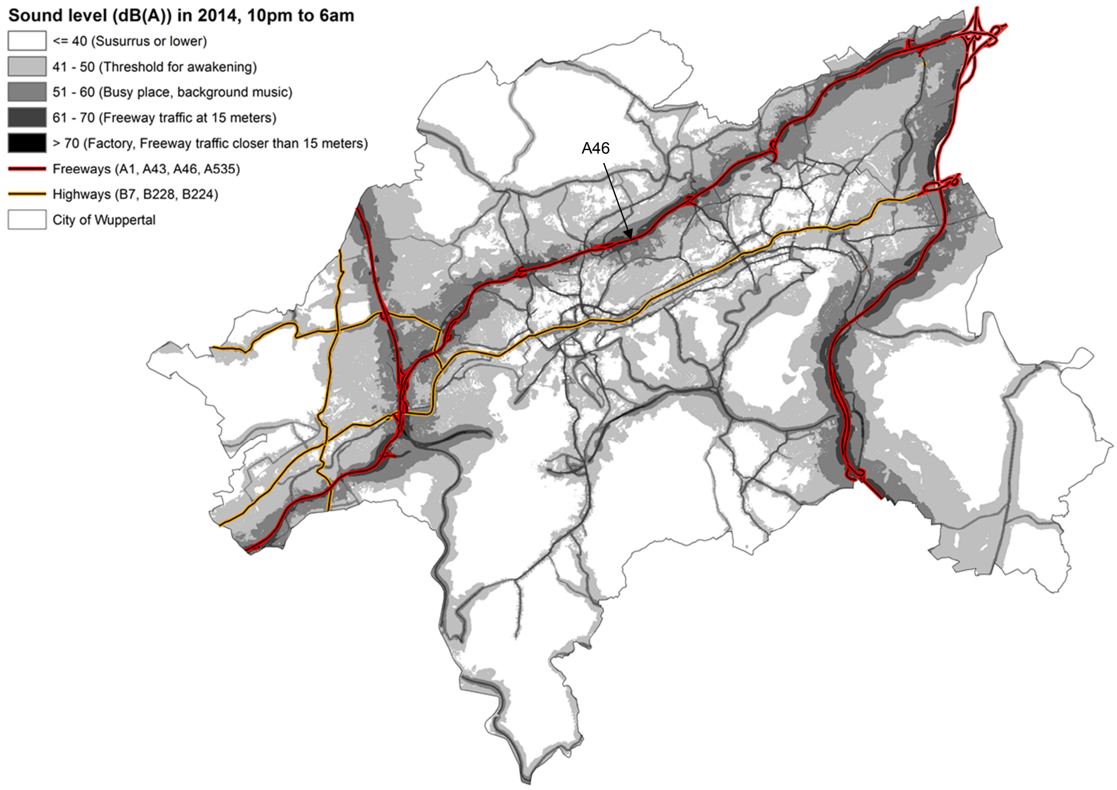
Besides the freeways, there are three high-traffic federal highways (Figure 3, yellow) and inner city roads – in particular used to avoid the busy freeway. And on top of the exposure to road traffic noise, there is railroad noise from train traffic as well as from Wuppertal's suspension railway (cf. Figure 4).

Figure 2 Sound level from road traffic at night in Wuppertal



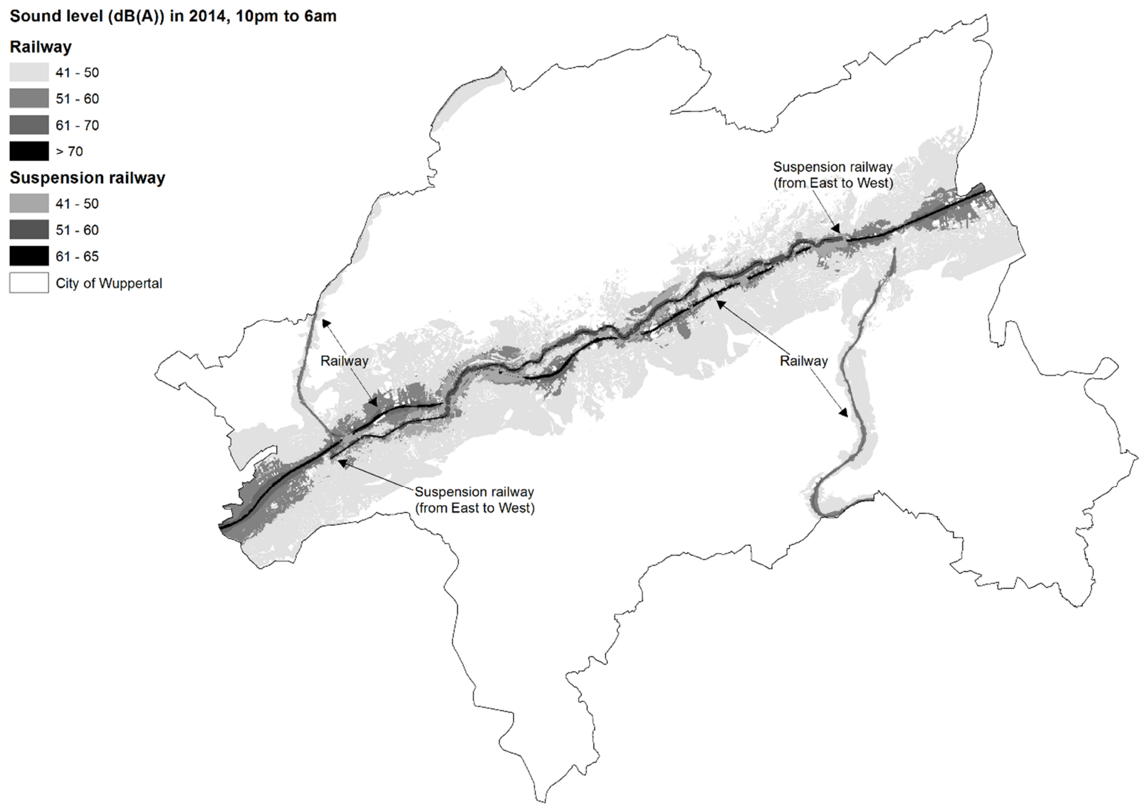
Data sources: City of Wuppertal, department for environmental protection, department of statistics, 2014

Figure 3 Sound level from road traffic at night in Wuppertal and major roads



Data sources: City of Wuppertal, department for environmental protection, department of statistics, 2014

Figure 4 Sound level from suspension railway and railway at night in Wuppertal



Data sources: City of Wuppertal, department for environmental protection, department of statistics, 2014; Federal Railway Authority, 2014

To determine the exposure to noise at night, we combine the raster information on noise presented in Figures 2, 3 and 4 and the addresses in Wuppertal. Raster data is processed within a Geo Information System and consist of millions of pixel information, each of them containing the sound level in dB(A). For each geocoded address, we generate a buffer with a radius of 30 meters and calculate the average and median sound level in dB(A) caused by traffic. In addition, we calculate the minimum and maximum sound level and the standard deviation within this radius (cf. Table 3). One potential limitation of this approach is the implicit assumption that children between the age of 0 and the school entry exam do not move to neighborhoods with lower or higher noise levels. Note that the noise levels children are exposed to are only known at the time of the SEnMed. While the assumption on relocations cannot be checked for the children in our data, we can use available information on all households with children younger than 6 years in Wuppertal on the city block level to describe the relationship between noise levels and moving households. A city block is a small administrative unit with on average about 140 residents (cf. Section 2.3). In 2015, about 14.43% of the children younger than 6 years moved within Wuppertal. For those who moved to different city blocks (13.59% of all children), the average noise level fell from 45.81 dB(A) to 45.08 dB(A). While the difference is quite small, it is statistically significant. Thus, when households move within the city, they tend to move to more quiet neighborhoods. In our analysis, therefore, the effect of noise on school readiness should be estimated consistently and, if at all, is more likely to be downward biased.

On average, the children in our data are exposed to a median noise level at night of 44.47 dB(A) from road traffic (cf. Table 2, column (2)), which is about 4 dB(A) above the recommended maximum night noise level for Europe (WHO 2009, p. XVII). The median noise level is, however, slightly below the legally required upper bound of 49 dB(A) for new or extended freeways (BMVI 2015). Yet some children are exposed to noise levels of up to 81 dB(A) at night (cf. Table 2, column (4)). This corresponds to the sound level of a train at 15 meters distance and can possibly cause hearing damage.

Table 2 Noise exposure of children at night, road traffic, different measures

	(1)	(2)	(3)	(4)	(5)
Statistics	Average noise level at night in dB(A) within a 30m radius	Median noise level at night in dB(A) within a 30m radius	Minimum noise level at night in dB(A) within a 30m radius	Maximum noise level at night in dB(A) within a 30m radius	Std. Dev. of noise level at night in dB(A) within a 30m radius
Mean	44.05	44.47	35.98	50.85	4.30
Std. Dev.	8.19	8.75	6.14	10.76	2.74
Minimum	17.58	17.50	9.00	21.00	0.45
p1	25.23	25.50	20.00	28.00	1.10
p25	37.61	37.50	32.00	42.00	2.17
p50 (Median)	43.34	43.00	35.00	50.00	3.30
p75	50.96	52.00	39.00	61.00	5.99
p99	60.06	62.00	52.00	70.00	11.77
Maximum	66.97	66.50	60.00	81.00	13.33
n	5,561	5,561	5,561	5,561	5,561

Data sources: City of Wuppertal, department for environmental protection, 2014; own calculations

In addition to road traffic, children living close to the suspension railway or federal railway are exposed to more than one source of noise. This in particular applies to children living in the valley axis with the major roads and railroads and where the population density is highest (cf. Figure 3, 4, and 5). To calculate the extent of noise emanating from all sources, we use the additive formula for m independent sources, where L is the sound level:

$$L_{\Sigma} = 10 \cdot log_{10}\left(10^{\frac{L_1}{10}} + \cdots + 10^{\frac{L_m}{10}}\right) \text{dB} \qquad (1)$$

With those three sources of ambient noise, children suffer from average noise levels of about 47.18 dB(A) at night, which is more than 7 dB(A) louder than recommended (WHO 2009). Note that for humans, an increase in sound pressure of about 10 dB(A) is perceived to be twice as loud.

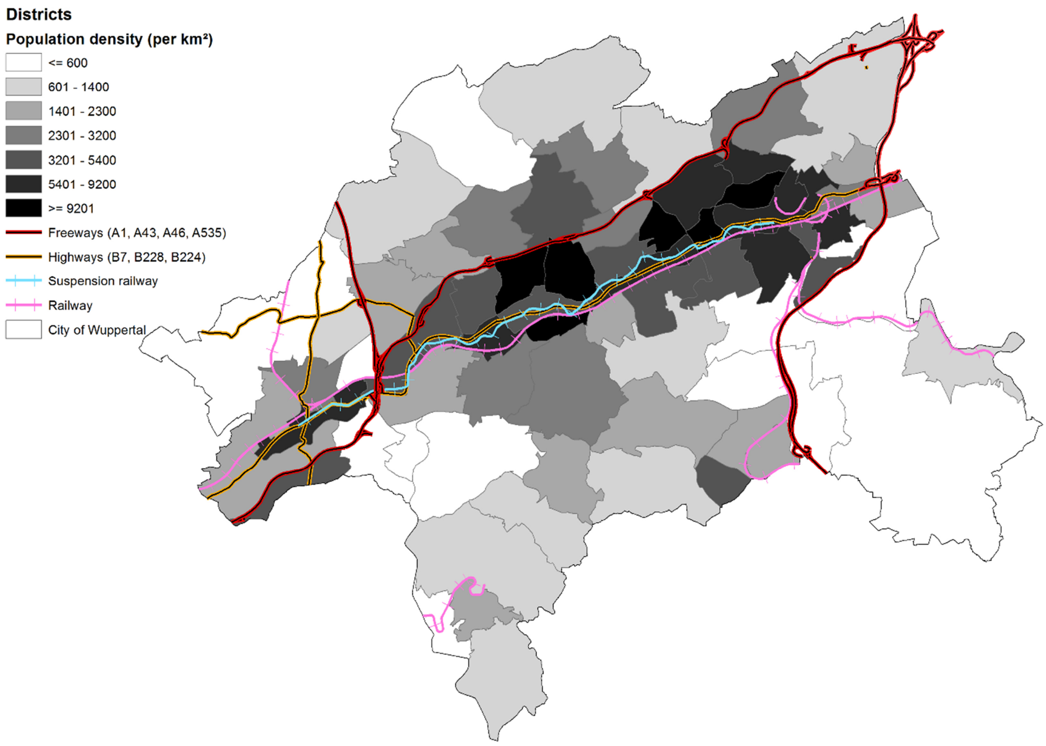
Table 3 Median noise level at night in dB(A) within a 30m radius by source

	(1)	(2)	(3)	(4)
Statistics	Road traffic	Suspension railway	Railway	All sources
Mean	44.47	4.51	25.52	47.18
Std. Dev.	8.75	13.54	22.47	8.37
Minimum	17.50	0.00	0.00	17.50
p1	25.50	0.00	0.00	25.50
p25	37.50	0.00	0.00	42.21
p50 (Median)	43.00	0.00	40.50	46.64
p75	52.00	0.00	43.82	53.27
p99	62.00	52.13	61.93	64.60
Maximum	66.50	59.04	72.13	75.00
n	5,561	5,561	5,561	5,561

Note: Noise from suspension railway and railway traffic is taken into account only if it exceeds 40 dB(A).

Data sources: City of Wuppertal, department for environmental protection, 2014; own calculations

Figure 5 Population density in Wuppertal's districts and major roads



Data source: City of Wuppertal, department for environmental protection, department of statistics, 2014; Federal Railway Authority, 2014

2.3. Socioeconomic status

The SEnMed and the noise data are merged with the data on socioeconomic status on the city block level. A city block is a small administrative unit with on average about 140 residents. In 2013, Wuppertal had 2,442 inhabited city blocks. The data provides detailed information on ethnicity, employment and welfare dependency. Clearly, the city block data is no individual level data. However, it indicates the probability of being member of a social group. For instance, if 20% of the children in a given city block live in low-income families, a child living in this city block is said to have a 20% probability of living in a low income family.

Enriching the data by city block information is important because the SEnMed data does not include individual level information on socioeconomic status. Thus, following earlier work (Makles/Schneider 2016, Schneider et al. 2012), the city block information is used as a proxy for a child's socioeconomic status. We describe the residential environment by variables like the risk of poverty (defined as the share of welfare-dependent private households[8]), the unemployment rate and the share of immigrants. Table 4 reports descriptive statistics for the city block variables. For instance, the average share of welfare recipients with children in a city block is 31.13% and the average share of immigrant children is 55.80%.

Table 4 City block data

Variable	Mean	Std. Dev.	Minimum	Maximum
% immigrants per city block	36.25	19.92	0.00	100.00
% immigrants below age 6 per city block	55.80	27.56	0.00	100.00
% unemployed adults per city block	9.70	6.40	0.00	55.71
% of welfare recipients per city block	18.96	14.08	0.00	86.67
% of welfare receiving households with children in city block	31.13	21.93	0.00	100.00
% of single family houses in city block	37.48	33.71	0.00	100.00

Data source: City of Wuppertal, department of statistics, 2014, Federal Railway Authority, 2014; own calculations

For the following empirical analysis, we generate a neighborhood index from the city block information. The index comprises the following variables weighted by principal factor analysis: share of immigrants, share of immigrant children under the age of six, employment share for employees with monthly income above €400, unemployment share, share of welfare recipients, share of households with children receiving welfare and share of unemployable adults. This approach is useful and valid as most of the variables are highly correlated. A higher value of the neighborhood index indicates lower social status.

3. Empirical strategy

The effect of traffic noise on school readiness is assessed by using two cohorts of preschool children discussed in section 2.1 and computing the one-dimensional factor of school readi-

[8] In Germany, people in need receive benefit payments either because they are (1) long-term unemployed, or (2) unemployable, or (3) employed but with an income below subsistence level.

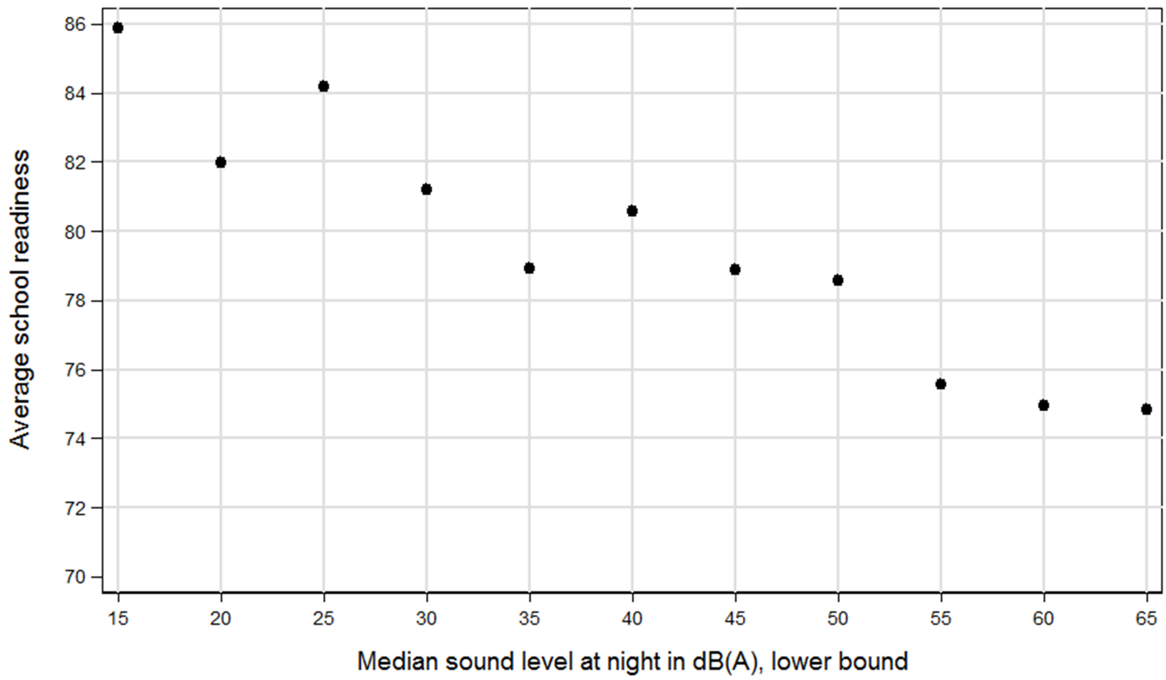
ness discussed above. The identification strategy to determine causal effects of traffic noise is explained in detail in the following sections.

3.1. Regression analysis

We start the analysis by looking at the effects of noise on school readiness with unconditional correlations. For example, Figure 6a shows a strong negative correlation between road traffic noise at night and school readiness. Children exposed to lower sound levels perform substantially better on the school readiness tests than children living in noisy environments.

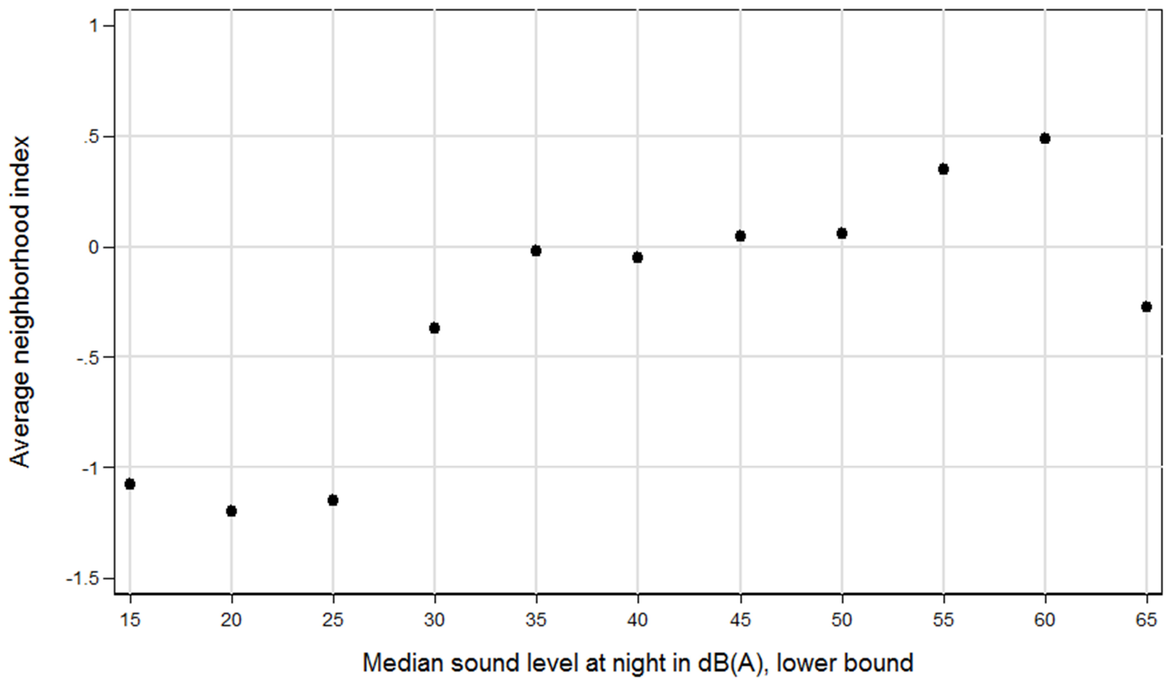
However, this is descriptive and only part of the story, because of another correlation shown in Figure 6b: the correlation between the exposure to road traffic noise and the neighborhood index. Perhaps not too surprisingly, the positive correlation suggests a noisier environment in poorer neighborhoods. This is in line with the literature, which shows effects of emissions on housing values (Currie et al. 2015, Boes/Nüesch 2011). And finally, Figure 6c suggests lower test scores in poorer neighborhoods. Thus, acknowledging the simple correlation between noise and test scores cannot be interpreted as causal and we need to develop a convincing identification strategy to estimate causal effects.

Figure 6a Correlation between school readiness and median sound level from road traffic at night in dB(A)



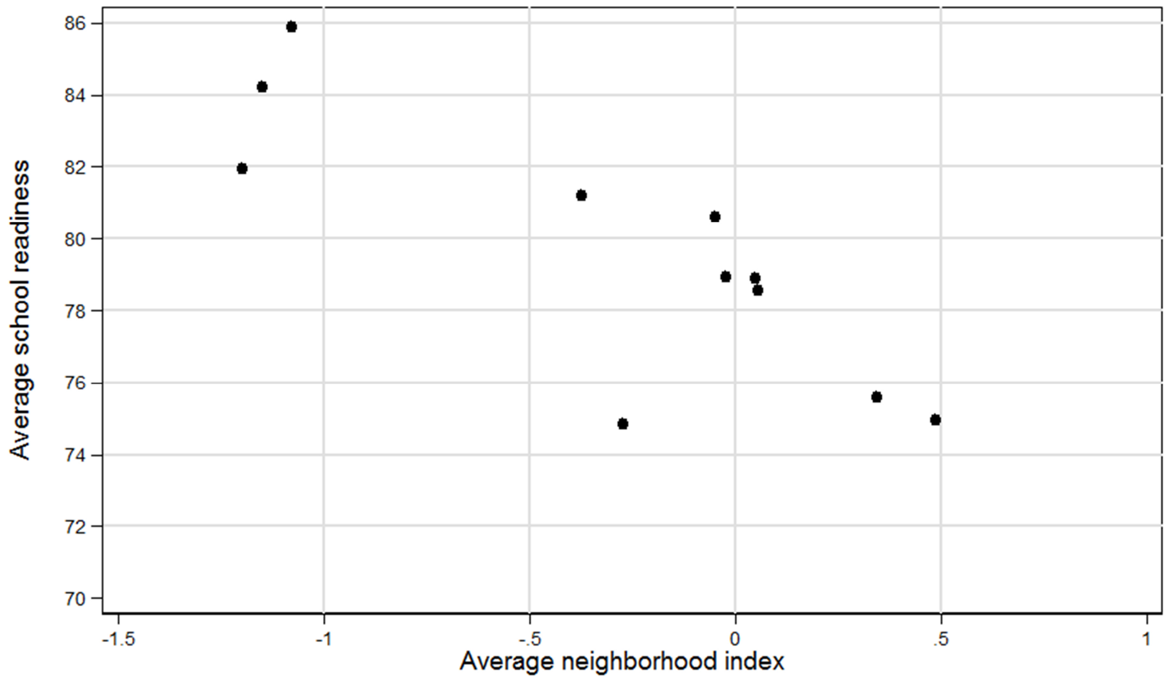
Data source: City of Wuppertal, health department, 2015; department of statistics, 2014

Figure 6b Correlation between the neighborhood index and median sound level from road traffic at night in dB(A)



Data source: City of Wuppertal, health department, 2015; department of statistics, 2014

Figure 6c Correlation between school readiness and the neighborhood index



Data source: City of Wuppertal, health department, 2015; department of statistics, 2014

3.1.1. Linear model and potential omitted variable bias

The equation to be estimated is

$$y_{it} = \alpha_i + \lambda_t + \beta X'_{it} + \rho n_{it} + \gamma B'_{it} + e_{it} \qquad (2).$$

In eq. (2), y_{it} is the outcome variable, i.e. school readiness of student i in cohort t, X_{it} is a vector of observed individual variables, like migration background, gender, number of siblings, time in kindergarten, immunization record, early health conditions, or the neighborhood variables. α_i is unobserved innate ability. The variable n_{it} is our measure of noise exposure, e.g. the median sound level of traffic noise within a radius of 30m. B_{it} is the unobserved family background, like the parents' valuation of education, the parents' educational background or the valuation of a quiet living environment. λ_t is a cohort fixed effect and e_{it} is the error term. Eq. (2) can be estimated by OLS which yields a consistent and unbiased estimate of ρ, our coefficient of interest, as long as the unobserved B_{it} is not correlated with the exposure to noise, which, however, cannot be ruled out. The potential omitted variable bias can be written as

$$E[\hat{\rho}] = \rho + \gamma\delta_{Bn}, \qquad (3)$$

where δ_{Bn} is the vector of coefficients obtained from the regression of B_{it} on n_{it} (Angrist/Pischke 2009). We expect unobserved family background to be negatively related to noise, because high income individuals can afford quiet housing and are willing to pay for less noise exposure, thus $\delta_{Bn} < 0$. In eq. (2) is $\gamma > 0$, because higher status correlates positively with higher school readiness. Thus, the estimated coefficient $\hat{\rho}$ in (2) tends to overestimate the true negative effect of noise on school readiness.

Moreover, innate ability α_i is also unobserved which could be of potential concern since we have no panel data. But, the problem of omitted variable bias due to unobserved individual ability is not substantial in the present setting as long as it can be assumed that innate ability is not correlated with the way in which noise affects cognitive development. In other words, noise is assumed to affect children of high ability just as it affects children of lower ability.

The issue of unobserved innate ability known from the returns to education literature comes up again, however, when estimating another important relationship: the effect of time spent in kindergarten. The returns to education literature deals with two potential sources of bias in this context: the omitted variable bias because of missing controls, like educational preferences, and the problem that unobserved ability affects both the demand for education as well as the outcome. The second source of endogeneity is not relevant in this paper. It is uncritical to assume that parents in Germany enroll their children in kindergarten regardless of the child's ability. However, (unobserved) parental educational preferences as well the need of child care might be important. It is unclear whether ambitious parents demand more time in kindergarten or less, as kindergarten in Germany is not thought to be part of the schooling system; there is no curriculum and attendance is voluntary. But more importantly, parents choose a kindergarten that fits their preferences for kindergarten quality. Thus, the potential bias due to unobserved kindergarten quality needs to be addressed.

3.1.2. Identification strategy

In a first step, we control for several observables by including comprehensive background information from our rich data. The background information is available on the individual as well as on the neighborhood (city block) level and can reduce the omitted variable bias resulting from missing socioeconomic controls on the family level. However, educational preferences and the child's ability cannot be proxied by neighborhood information. And while time spent in kindergarten is known, the effect of kindergarten duration is not easily identified because in addition to unobserved parental input the (unobserved) quality of the kindergarten will affect cognitive development.

As noted above, children are enrolled in kindergarten for two reasons: First, parents need day care and second, kindergarten has an educational purpose. Parents with strong preferences for education will choose a kindergarten that fits their educational needs best. Our strategy to deal with potential omitted variable bias in this case is as follows: First, besides using the available individual level information, we control for characteristics on the city block level. The information allows controlling for the ethnic composition, unemployment, and welfare dependency rates. It can be reasonably assumed that families within a city block are a fairly homogenous group. Thus, the unobserved part of the socioeconomic background might not be as important to begin with if educational preferences are correlated with the observed characteristics of the families, as is reasonable to assume. We also include a large set of individual level control variables which are related to cognitive development. For example, in addition to migration background and gender, we control for maturity effects, and family related variables, like the number of siblings or the mother's or father's country of birth. We also control for health conditions or the number of health check-ups since birth. In addition, the data comprises information on birth weight which is used as a proxy for early health conditions.

In a next step and more importantly, we control for kindergarten fixed effects, μ_k, to account for unobserved kindergarten quality. Furthermore, kindergarten fixed effects allow controlling for the socioeconomic composition of the kindergarten as well as noise exposure in kindergarten during the day. As mentioned in the introduction, noise exposure in kindergarten might be substantial but also different across kindergartens. Since n_{it} measures exposure to noise at night and most children attend a kindergarten during the day, relying on noise at night only results in measurement error if the noise level at night is a poor proxy for overall (day and night) exposure to noise. Our data includes information on noise during the day and at night. It turns out that these noise levels at the children's home are highly correlated.

In our setting, kindergarten fixed effects serve yet another purpose. Families are free to choose a kindergarten, and kindergartens are fairly segregated (Makles/Schneider 2016). The diversity of kindergarten quality in Germany is large, since no curriculum for preschool education exists. Kindergartens can be run by the municipalities, the church or by private initiatives (with or without public subsidies). Thus, the choice of the kindergarten also reflects the socioeconomic status and in particular the unobserved educational preferences of the families. This helps identifying the causal effect of noise on child development. Including kindergarten fixed effects is expected to reduce the estimated negative noise effect, as we tend to overestimate the detrimental effect due to the omitted variable bias. And finally, as the child's prospective primary school is known as well, additional school fixed effects, μ_s, are included in the analysis to even better control for parental educational preferences. Hence, the equation to be estimated is modified to

$$y_{itks} = \alpha_i + \mu_k + \mu_s + \lambda_t + \beta X'_{itks} + \rho n_{itks} + \gamma B'_{itks} + e_{itks} , \qquad (4)$$

where the index k denotes the kindergarten and s denotes the school.

Besides identifying the noise effect, ρ, kindergarten fixed effects also help to identify the effect of kindergarten attendance. Recall that family preferences play a role when deciding on the duration of kindergarten as well as the choice of the kindergarten. Those preferences are accounted for by kindergarten and school fixed effects. Thus, identification of the kindergarten duration effect on school readiness stems from kindergarten and school fixed effects. Alternatively, instead of using kindergarten fixed effects, we use retrospective information on the average kindergarten achievement in school readiness to measure kindergarten quality. Nonetheless, full information on the child's innate ability, educational preferences and educational inputs is missing; that might well affect the child's cognitive outcome and also the choice of residence which in turn correlates with the noise level in the neighborhood. Therefore, some concerns about the exogeneity of exposure to noise at night remain even after controlling for the full set of variables and kindergarten and primary school fixed effects or the kindergarten quality. Hence, in the following – but this is merely meant as a robustness check – we apply an instrumental variables approach and test for endogeneity.

3.1.3. Robustness check

Since two variables are potentially endogenous, noise and time in kindergarten, both variables need to be instrumented for. Our instrument for noise at night is the standard deviation of noise at night within a radius of 100m (200m) around the addresses, i.e. the variation in the neighborhood. We use the exogenous variation in noise levels in the neighborhood to identify the causal effect of permanent ambient noise on cognitive development. To be a valid instrument, the instrument should correlate with noise but not affect a child's cognitive ability directly.

The main idea is to instrument the noise level at a child's home by using information on the neighbors. Noise levels are correlated within a neighborhood but there is no social sorting within a radius of 100m (200m). We argue that the standard deviation of noise exposure or the coefficient of variation within a neighborhood of 100m (200m) is variation that is exogenous with respect to socioeconomic status. Families indeed choose neighborhoods depending on the social composition and possibly the proximity to good kindergartens, schools and green space. In addition, higher status families might choose quieter environments. However, there is variation in noise exposure within a neighborhood that cannot be fully controlled. The idea is related to Cohen/Glass/Singer (1973), who compare children living in the same building but on different floors (cf. Section 1). Thus, families in the same neighborhood might be exposed to different levels of noise although they are of similar socioeconomic background and have similar educational preferences.

Time in kindergarten is instrumented by proxies for exogenous kindergarten supply and legal rules on kindergarten admittance. The supply of kindergarten is measured by the distance to the closest kindergarten. Legal rules help us to determine the theoretical kindergarten age, i.e. the duration in kindergarten given the child enters kindergarten on his or her third birthday. The theoretical kindergarten duration is used as an instrument, which has been proven to be valid in school age studies (Bedard/Dhuey 2006, Mühlenweg/Puhani 2010, Jürges/Schneider 2011). Unlike in school entry decisions, the rules are not as clear cut in case of kindergarten. However, children in our data are entitled to attend kindergarten at the age of three years. In addition, there is an older rule that the kindergarten year starts on August 1st and all new children enter kindergarten on August 1st. While this rule is not legally binding, it is still in practice and affects time in kindergarten depending on the month of birth. We therefore use assigned age (defined as 7 minus month of birth for children born between January and July and 19 minus month of birth for children born between August and December (c.f. Bedard/Dhuey 2006, p. 9)) as an additional instrument to describe the legal rules and to address month of birth effects.

Besides the mentioned potential endogeneity bias, we face another challenge. Traffic is not only the main source of noise in urban areas but also a major source of local air pollution. While noise data is available, the data on air pollution is not. Moreover, air pollution from traffic and noise are correlated. Hence estimating the pure noise effect, i.e. separating the noise and the air pollution effects, is not trivial and the possible effect of air pollution on cognitive development has to be discussed. As known from the literature cited above, air pollution has a strong detrimental effect on children's health, in particular on prematurity and low birth weight. The age group of preschool children studied here is most likely to be affected by respiratory diseases such as asthma or bronchitis or allergies. While the effect of those diseases on cognitive development is not clear (Currie 2009), it cannot be ruled out that air pollution is partially driving the effect. In the present paper, we cannot fully solve the problem but we present arguments that help to better understand the relationship of traffic, noise, pollution, and cognitive development.

3.1.4. Varying treatment definition

Finally, the existing studies on the effects of noise do not explicitly analyze the functional form of the relationship between noise and development. Noise is typically reported in decibel A-weighted which is non-linear in loudness. Thus, even if the relationship between dB(A) and child development, i.e. school readiness, is linear, the relationship between loudness (subjective perception) and development is not. We present some variations as a starting point for the discussion.

3.2. Cost-benefit analysis

To complete the analysis, we suggest an admittedly tentative cost-benefit analysis. As has been noted earlier, public funds are being spent on noise protection and legal rules force governments to engage in noise protection. While noise exposure might reduce cognitive development, kindergarten education enhances development. The costs of various noise protection measures are known. Once we have an estimate of the adverse effect of noise on cognitive ability and an estimate of the school readiness improving effect of kindergarten attendance, we can conduct a cost-benefit analysis. Hence, the main idea is to compensate the adverse noise effect by additional education, the cost of which is known.

For doing so, we need an estimate of the cost of noise protection, for instance the cost of a soundproof wall per km/year with depreciation period *T*, which we denote by C_{noise}. In addition we need an estimate of the reduction in ambient noise resulting from the measure of noise protection, $\Delta_{\text{dB(A)}}$. Those costs are compared with the cost of additional time in kindergarten C_{kiga}. With the estimated coefficients we can compute the relative effect on school readiness as $-\hat{\rho}/\hat{\beta}_{\text{kiga}}$. Hence $-\hat{\rho}/\hat{\beta}_{\text{kiga}}$ denotes the time spend in kindergarten (in months) that has the same effect on school readiness as a one dB(A) reduction in noise. Multiplied by C_{kiga} (per month), this gives the cost per child in kindergarten to match the effect of noise protection. Equating cost of noise protection per child and year to the alternative spending on kindergarten education, allows solving for the critical number of children to benefit from noise protection, *N*. This defines the breakeven point. Hence,

$$\frac{C_{\text{noise}}}{N} = -\Delta_{\text{dB(A)}}\left(-\frac{\hat{\rho}}{\hat{\beta}_{\text{kiga}}}\right)C_{\text{kiga}}$$

$$N = \frac{1}{\Delta_{\text{dB(A)}}}\frac{C_{\text{noise}}}{\hat{\rho}}\frac{\hat{\beta}_{\text{kiga}}}{C_{\text{kiga}}} \qquad (5)$$

The analysis is clearly simplifying at this point and partial in nature. However, we argue that this presents a very conservative estimate. First, the focus is on early childhood development. We know from the literature, that early childhood conditions are important for later life development. Hence, we tend to underestimate the benefit from noise protection. However, since we compare benefits from lower noise levels with effects from attending kindergarten, which is also thought to have a long term effect, the bias might not be severe after all. Second, and more importantly, we do not account for the effects on other individuals in the neighborhood. Adults, younger and older children benefit as well. In particular for the adult population, the evidence for severe health effects of noise is compelling (EEA 2014).

4. Regression results

4.1. OLS Estimates

Table 5 summarizes the regression results. As the dependent variable, our index of school readiness, is between 0 and 100, the effects of all variables can be interpreted as changes in school readiness in percentage points (or in %).

As argued above, we expect the adverse effect of noise measured by the median sound level from road traffic in dB(A) at night to be overestimated due to the omitted variable bias. In fact, the noise coefficient in our basic model without fixed effects (cf. Table 5, column (1)) is twice as large as the coefficient when accounting for kindergarten fixed effects (column (2)). The effect decreases from -0.168 to -0.083. However, it remains significant on the 1% level. Children living in noisy environments perform worse on the school entry examination than children living in quiet areas. Adding individual controls (column (3)) like kindergarten duration, gender and migration status reduces the estimated effect slightly. However, changes are not substantial and the effect of noise from road traffic on school readiness remains negative and significant at the 1% level. All included controls have the expected effect on school readiness. Immigrant status, for instance, has the expected strong negative effect whereas time spent in kindergarten has a positive effect.

To further control for individual characteristics and the families' socioeconomic status, we add additional controls along with health variables in model (4). The health variables include dummy coded information on low birth weight, overweight/obese, partial hearing loss, and reduced visual acuity and the number of medical screenings since birth. These variables indicate physical health which may affect school readiness and some of them also capture the socioeconomic status of the family. Socioeconomic status (SES) and some of the health variables chosen in the analysis are correlated. Higher SES children are less likely to be obese, have higher birth weight and are more likely to attend the recommended medical screenings. The model in column (4) also includes the neighborhood index which uses the city block data and describes the socioeconomic structure of the neighborhood as discussed in section 2.3. The index of low SES of the neighborhood has the expected negative and significant impact. Since high values represent low SES, low SES goes along with lower school readiness.

Table 5 Effects of noise on school readiness I: OLS

	(1)	(2)	(3)	(4)	(5)	(6)
Road noise	-0.1680***	-0.0826***	-0.0601***	-0.0461**	-0.0493**	
(at night, in dB(A))	(0.0244)	(0.0218)	(0.0207)	(0.0210)	(0.0212)	
Traffic noise (road, suspension railway, and railway)						-0.0557**
						(0.0219)
Duration kindergarten			0.2109***			
(in months)			(0.0212)			
Δ kindergarten				0.1538***	0.1518***	0.1540***
(Difference in months)				(0.0212)	(0.0204)	(0.0211)
Gender (male = 1)			-2.2952***	-2.5297***	-2.4445***	-2.5356***
			(0.3179)	(0.3142)	(0.2953)	(0.3142)
Migrant (yes = 1)			-5.6121***	-3.4493***	-3.3193***	-3.4396***
			(0.3930)	(0.4880)	(0.4822)	(0.4886)
Neighborhood index				-0.7594***	-0.8168***	-0.7283***
				(0.2240)	(0.2163)	(0.2271)
Cohort FE	YES	YES	YES	YES	YES	YES
Kindergarten FE	NO	YES	YES	YES	NO	YES
School FE	NO	NO	NO	YES	YES	YES
Additional controls	NO	NO	NO	YES	YES	YES
Observations	4,295	4,295	4,295	4,295	4,294	4,295
Kindergartens		184	184	184	183	184
Within R^2		0.0036	0.0969	0.1733		0.1734
Between R^2		0.1627	0.5222	0.6053		0.6015
Overall R^2	0.015	0.0143	0.1613	0.2633	0.2892	0.2630

Notes: Dependent variable is school readiness score; standard errors in parentheses are clustered at the kindergarten level; + $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; model (5) excludes kindergarten fixed effects and includes retrospective kindergarten achievement level in 2009/10, 2010/11, and 2011/12; additional controls are: age (below 69 months, above 73 months, reference is between 69 and 73 months), mother born in Germany, father born in Germany, single parent, number of siblings (0, 2, 3, 4 or more, reference is 1 sibling), low birth weight, obesity/overweight, (severe) underweight, non-presentation of health record, no U8 medical screening conducted, non-presentation of immunization record, no tetanus vaccination, reduced visual acuity, partial hearing loss; neighborhood index includes the following city block information (weighted by principal factor analysis): share of immigrants, share of immigrant children under the age of six, employment share, unemployment share, share of welfare recipients, share of households with children receiving welfare, and share of unemployable adults

Finally, we need to address another variable: the duration in kindergarten. Since kindergarten is an educational institution that supports children's cognitive development, time spent in kindergarten is an important variable to explain school readiness. But clearly, the variable has two potential problems (cf. Section 3.1). First, we are aware of the aforementioned omitted variable bias, which we address by kindergarten and school fixed effects as well as the individual and neighborhood controls in model (4). Second, the variable might measure maturity effects because children who are older at the school entry exam might outperform the younger peers. Even though this is not a systematic problem in Wuppertal, since children are invited to the school entry exam according to birth date and are about 69 to 73 months old when examined, we address this issue in model (4) by adding two dummy variables for children that are younger than 69 months and children who are older than 73 months. In addition, we compute the theoretical kindergarten duration (age at examination minus 36 months) and use the variable Δ kindergarten which is the difference between time in kindergarten and the theoretical time in kindergarten in the regression. The effect of time in kindergarten drops to 0.154 in model (4) but remains significant at the 1% level. In model (5) we use retrospective average kindergarten performance as discussed in Section 3.1.2 on the SEnMed instead of simple kindergarten fixed effects. The results are basically unchanged.

In models (1) to (5) we focus on noise from road traffic only. But, since noise pollution does not only result from road traffic, but also includes railroads and other rail vehicles, like the suspension railway in Wuppertal, we compute the overall noise level as described in Section 2.3 and use it as the treatment variable in column (6). The effect of ambient noise on school readiness is now slightly stronger with -0.056 than the effect of road traffic only. The coefficients of the controls remain essentially unaffected.

As discussed earlier, vehicle traffic is not only emitting noise but also air pollutants, which affect health and hence indirectly possibly cognitive development of children. Since noise and pollution from road traffic are correlated, we first look at the correlation between road noise and pollution related diseases. The results are summarized in Table 6. It turns out that none of the diseases is significantly correlated with our measure of road noise, which supports our estimation strategy in Table 5. In addition to the information on road noise, we use information on railway noise, which does not produce local air pollution. Hence in model (5) we estimate a full model similar to Table 5, column (4) including railroad noise only instead of road noise as our treatment variable. Note that the number of observations drops to 2,419 because fewer children are affected from railroad noise (cf. Section 2.2) than from road noise. Thus the estimates are not comparable. However, we estimate a negative and significant coefficient, which is even larger in magnitude compared to the estimated effect in Table 5. We interpret this as support of our results: the estimated coefficients of the noise variable capture in fact the effect of noise on cognitive development.

Table 6 Robustness check

	(1)	(2)	(3)	(4)	(5)
Dependent variable	Allergic rhinitis	Bronchitis	Asthma	Any disease of the respiratory system	School readiness
Road noise	-0.0004	-0.0002	-0.0000	-0.0006	
(at night, in dB(A))	(0.0002)	(0.0003)	(0.0002)	(0.0004)	
Railway noise (suspension					-0.0952**
railway and railway only)					(0.0368)
Δ kindergarten	-0.0002	-0.0003	0.0002	-0.0002	0.1598***
(Difference in months)	(0.0002)	(0.0004)	(0.0002)	(0.0005)	(0.0298)
Gender (male = 1)	0.0045	-0.0017	0.0026	0.0057	-2.5282***
	(0.0033)	(0.0053)	(0.0038)	(0.0069)	(0.4364)
Migrant (yes = 1)	0.0019	0.0057	0.0022	0.0058	-2.8768***
	(0.0057)	(0.0080)	(0.0053)	(0.0100)	(0.5398)
Neighborhood index	0.0017	0.0060	0.0011	0.0067	-0.5611^{+}
	(0.0025)	(0.0043)	(0.0024)	(0.0046)	(0.2864)
Cohort FE	YES	YES	YES	YES	YES
Kindergarten FE	YES	YES	YES	YES	YES
School FE	YES	YES	YES	YES	YES
Additional controls	YES	YES	YES	YES	YES
Observations	4,295	4,295	4,295	4,295	2,419
Kindergartens	184	184	184	184	166
Within R^2	0.0205	0.0237	0.0141	0.0236	0.1845
Between R^2	0.0002	0.0068	0.0016	0.0270	0.4533
Overall R^2	0.0142	0.0154	0.0072	0.0189	0.2292

Notes: standard errors in parentheses are clustered at the kindergarten level; + $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; additional controls are: age (below 69 months, above 73 months, reference is between 69 and 73 months), mother born in Germany, father born in Germany, single parent, number of siblings (0, 2, 3, 4 or more, reference is 1 sibling), low birth weight, obesity/overweight, (severe) underweight, non-presentation of health record, no U8 medical screening conducted, non-presentation of immunization record, no tetanus vaccination; neighborhood index includes the following city block information (weighted by principal factor analysis): share of immigrants, share of immigrant children under the age of six, employment share, unemployment share, share of welfare recipients, share of households with children receiving welfare, and share of unemployable adults

4.2. IV Estimates

As discussed in Section 3.1, the data might not include all desirable individual level information like parents' education or educational preferences. While we are confident that our identification strategy identifies the causal effect of noise on school readiness, we suggest a robustness check and perform an IV estimation approach using the instruments as discussed in section 3.1.3 and check the exogeneity of the treatment assumption in the models of Table 5.

Table 7 Effects of noise on school readiness II: IV

	(1)	(2)	(3)	(4)
Road noise	-0.153***	-0.0629+		
(at night, in dB(A))	(0.0401)	(0.0378)		
Traffic noise (road, suspension			-0.202***	-0.0731+
railway, and railway)			(0.0394)	(0.0392)
Duration kindergarten	0.475***	-0.124	0.576***	0.124
(in months)	(0.154)	(0.217)	(0.157)	(0.196)
Gender (male = 1)		-2.814***		-2.535***
		(0.362)		(0.358)
Migrant (yes = 1)		-4.924***		-4.491***
		(0.497)		(0.517)
Neighborhood index		-1.138***		-0.911***
		(0.333)		(0.315)
Cohort FE	YES	YES	YES	YES
Kindergarten FE	YES	YES	YES	YES
School FE	NO	YES	NO	YES
Additional controls	NO	YES	NO	YES
Observations	4,293	4,293	4,125	4,125
Kindergartens	182	182	182	182
Sanderson-Windmeijer F-test	18.36	7.70	10.18	4.59
equation 1 (duration kindergarten)	$F(4,181)$	$F(4,181)$	$F(8,181)$	$F(8,181)$
Sanderson-Windmeijer F-test equation 2 (noise)	195.12	196.22	87.36	107.46
χ^2-Test on endogeneity (p-value)	9.202	3.834	15.780	1.069
	(0.01)	(0.1471)	(0.0004)	(0.586)

Notes: See Table 5; excluded instruments (depending on the endogenous variable): standard deviation of noise (road, railway, suspension railway) in a radius of 100 and 200 meters, assigned age, theoretical kindergarten duration.

Table 7 summarizes the results for this robustness check. In model (1), the only controls are kindergarten duration, the kindergarten fixed effects and the cohort fixed effect. Road noise as well as kindergarten duration affect school readiness significantly. The reported first stage multivariate F-statistics are the Sanderson-Windmeijer test on weak identification (Sanderson/Windmeijer 2015). The test on endogeneity which compares OLS with IV rejects the null hypothesis of no endogeneity. Model (2) is the full model as specified in Table 5, column (4). The coefficients drop and the coefficient for kindergarten duration is no longer significant. The noise variable drops and is close to the OLS specification in Table 5 but only marginally significant. The test on endogeneity no longer rejects the null hypothesis of exogeneity. Hence our conjecture that the specification in Table 5, column (4) adequately addresses the omitted variable bias is supported. In models (3) and (4), the noise variable includes noise from road traffic, railway traffic and the suspension railway. The conclusions are similar to the model with road traffic only. While our models pass the tests on identification and the instruments are not weak according to the method proposed in Sanderson/Windmeijer (2015), the null hypothesis of exogeneity of the regressors cannot be rejected in the full models. Thus, our strategy to identify the effect by a saturated model with kindergarten and school fixed effects (cf. Table 5, column (4) and (6)) is supported.

4.3. Estimates for different specifications of the treatment variables

Table 8 extends the analysis to different specifications of the noise variables. Noise is measured in dB(A) which is not a linear measure of experienced loudness. An increase of 10 dB(A) amounts to a doubling of the noise level. While there is no exact formula to translate dB(A) in loudness, the approximate relationship is

$$l = 10^{([L_{\mathrm{dB(A)}} - 28]/33.22)} \qquad (6)$$

Since the relationship between dB(A) and loudness is not linear, the effect of noise on child development is not linear either, even if the effect of noise measured in dB(A) on school readiness is linear. Moreover, low levels of noise are not harmful, but high levels are. Identifying a threshold beyond which noise is harmful is clearly beyond the scope of this study. However, in Table 8 we provide some first evidence on how various measures of noise affect school readiness. The models reported there include the controls as in Table 5, model (4). Only the noise variable differs between the models. In column (1) the noise variable is a dummy which has a value of one if the noise level exceeds 50 dB(A), a commonly used threshold for adverse health effects of noise. The effect is strong, negative and significant. Compared to the effect of kindergarten attendance, the effect is more than 6 months in kindergarten or about one half of the gender difference. Put differently, children who are exposed to permanent high levels of noise at night are about half a kindergarten year behind. In model (2) the measure of loudness (cf. eq. (6)) is used, and specification (3) uses the level of traffic noise from all sources instead of road noise only. The effects of (1) and (3) are similar. In model (4) we finally estimate a spline model with 3 splines (the noise is measured in dB(A) and includes all sources (road, railway and suspension railway)). The significant effect is only at the last spline. The first two splines are insignificant. Thus, the adverse effect of noise does in fact occur only at higher levels of noise. Public spending on noise reduction might therefore be well advised to focus on regions with severe ambient noise levels with more than 50 dB(A) at night.

5. How much to spend on noise abatement?

Noise protection is high on the political agenda. While the cost of investing in noise abatement should be readily available, the benefits are hard to grasp. At this point, and using our data, we cannot provide a full cost-benefit analysis. However, we can use our results to compare the cost of the adverse effects of ambient noise on child development with the cost of noise protection measures such as soundwalls or quiet pavement. Using our estimates of the adverse effects of noise on child development in Table 5, column (4), we can compute the breakeven points as discussed in Section 3.2.

Table 8 Effects of noise on school readiness III: OLS with varying treatment variable

	(1)	(2)	(3)	(4)
Road noise > 50 dB(A) (at night)	-0.9592**			
	(0.3885)			
Loudness (road noise)		-0.1756**		
		(0.0797)		
Traffic noise > 50 dB(A) (road and railways)			-0.8632**	
			(0.3420)	
Spline 1 (traffic noise)				0.0290
				(0.0507)
Spline 2 (traffic noise)				-0.0325
				(0.0638)
Spline 3 (traffic noise)				-0.1455**
				(0.0697)
Δ kindergarten (Difference in months)	0.1537***	0.1539***	0.1545***	0.1548***
	(0.0211)	(0.0211)	(0.0211)	(0.0211)
Gender (male = 1)	-2.5308***	-2.5269***	-2.5289***	-2.5308***
	(0.3130)	(0.3143)	(0.3131)	(0.3136)
Migrant (yes = 1)	-3.4455***	-3.4531***	-3.4476***	-3.4519***
	(0.4850)	(0.4874)	(0.4859)	(0.4884)
Neighborhood index	-0.7683***	-0.7602***	-0.7596***	-0.7279***
	(0.2214)	(0.2239)	(0.2233)	(0.2266)
Cohort FE	YES	YES	YES	YES
Kindergarten FE	YES	YES	YES	YES
School FE	YES	YES	YES	YES
Controls	YES	YES	YES	YES
Observations	4,295	4,295	4,295	4,295
Kindergartens	184	184	184	184
Within R^2	0.1736	0.1734	0.1734	0.1742
Between R^2	0.6045	0.6052	0.6052	0.6011
Overall R^2	0.2640	0.2636	0.2633	0.2639

Notes: See Table 5

Table 9 summarizes the results for examples of noise abatement methods: noise protection embankment and soundwalls as protection measures at highways and quiet pavement and 30 km/h zones in inner city areas. In addition, we do calculations for soundproof windows, a passive noise protection method. Soundproof windows and 30 km/h zones are suitable to reduce noise from inner city roads, where other abatement measures like soundproof walls are not an option.

Table 9 Breakeven point of noise protection

	Embankment	Soundwall	Quiet pave-ment	30 km/h zone (night only)	Soundproof window
Costs per m² in Euros	90	326	23.12		613
Costs per sign in Euros				488	
× width 20m			×		
× length 1km	×	×	×	×	
× height 6m	×	×			
× area 12m²					×
Total costs	540,000/km	1,956,000/km	462,400/km	19,520/km	7,356/flat

Benchmarks:	
Estimated effect of one month in kindergarten on school readiness, β_{kiga}	0.15
Estimated effect of one dB(A) road noise on school readiness, ρ	-0.05
Costs of one kindergarten month in Euros per child	508.00

Breakeven points: number of children to benefit from noise protection per year (cohort) and km (per year and flat for soundproof windows)

		Embankment		Soundwall		Quiet pave-ment		30 km/h zone (night only)		Soundproof window	
		Depreciation in years									
		20	25	15	20	5	8	15	20	20	25
Noise reduction	-20									0.11	0.09
	-15									0.14	0.12
	-10	16	13	78	58	55	35			0.22	0.17
	-8	20	16	97	73	69	43				
	-7							1.10	0.82		
	-5	32	26	155	116	110	69	1.54	1.15		
	-3							2.56	1.92		

Notes: Own computations based on public spending on noise protection at federal roads in 2014 as reported in BMVI (2015) except costs for 30 km/h zones. Costs for 30 km/h zones based on estimated costs provided by the city of Wuppertal. Costs for expertise, travel costs, enforcement or benefits from reduced accidents and air pollution are not included. The costs per km are based on a sign density in central areas of about 40 per km (20 in each direction). Parameters β_{kiga} and ρ as estimated in Table 5, column (4).

Provided the resulting reduction in noise is 10 dB(A) and the depreciation period is 20 years, the breakeven point for an investment in noise protection embankment (one side of the road) is reached for 16 children per km and cohort. With an investment in soundwalls, the number of children is 58. Assuming a shorter depreciation period of 15 years only, the number of children rises to 78. Quiet pavement is less expensive, although the costs vary depending on the location (BMVI, 2015) and the durability is still uncertain. For a depreciation period of 8 years the breakeven point is reached at 35 children (per km). If the pavement is less durable, i.e. only 5 years, the number of children is 55. As shown in Table 8, those figures are less favorable, if the noise reduction is only 8 or 5 dB(A). Given a reduction in noise of 5 dB(A) only and a depreciation period of 15 years, the soundwall (one side of the road) breaks even at 155 children per cohort and km.

Establishing 30 km/h zones in inner city areas comes at lower monetary costs but it is very unpopular as it slows down traffic. However, as argued in van Benthem (2015), a cost benefit analysis strongly supports reduced speed limits (on freeways) when including travel speed, accidents, and health effects of pollution in the analysis. Our approach is less ambitious. The costs in Table 9 only include costs for setting up the street signs. Additional time costs or enforcement costs are not included. The same applies to additional benefits from reduced local air pollution or fewer accidents. Reducing speed limit from 50 km/h to 30 km/h within an inner city residential area reduces the noise level between 3 dB(A) and 7 dB(A). Assuming a reduction of 3 dB(A) and a depreciation period of 20 years, 30 km/h signs break even at 1.92 children per cohort and km. But clearly, without having a good estimate of the time costs, this estimate is not reliable. On the other hand, since driving through inner city residential areas is typically short distance, additional time costs might be low.

An alternative to active noise protection are passive noise protection measures, for instance soundproof windows. Soundproof windows can absorb additional 10 dB(A) or even up to 25 dB(A) compared to a standard window[9] and cost on average 613 Euros/m^2 (BMVI 2015).[10] Hence, soundproof windows effectively reduce noise form inner city traffic at night. Assuming an average flat with about 4 to 6 windows, an area of 12m² has to be equipped with soundproof windows. With a noise reduction of 20 dB(A) and a depreciation period of 25 years this investment breaks even at 0.09 children per flat and year. In the less favorite case with a depreciation period of 20 years and a noise reduction of 10 dB(A), the number is at 0.22 children per flat and year. Put differently, in the less favorite case the windows have to protect a newborn every 4.5 years per flat from noise. Given that about 150.000 households are exposed to severe inner city traffic (about ¾ of all flats in Wuppertal), even in the favorite case (-20 dB(A), 25 years) the breakeven point is reached at 13,500 children per cohort, which is far more than a cohort size in Wuppertal. Or alternatively, given that the costs of soundproof windows are 7,356 per flat and the noise abatement of 20 dB(A) has the same effect as 6.66 month in kindergarten, the benefits are worth 3,383 Euros. Hence if there are 2.17 children per family and flat (over a time period of 25 years), the investments breaks even.

These computations can only serve as a starting point for the discussion. There are certainly some caveats besides the limited selection of noise abatement instruments in the analysis. For instance, the depreciation periods are estimates. If quiet pavement is not as long lasting as 5 years, the results change. Also, when looking at the cost of embankments, we underestimate the true costs, because in an urban area like Wuppertal, embankments are even more expensive than soundwalls simply because of limited space. In fact, in densely populated areas embankments are not a realistic option in the first place and a mix of different measures, like quiet pavement, soundproof windows and 30 km/h zones has to be discussed. But keeping the limitations in mind, the computations show that breakeven points can be calculated for

[9] According to the VDI guideline 2719 of the German Engineers Association (Verein Deutscher Ingenieure)
[10] Note that additional cost for ventilation are not included.

all types of active and passive noise abatement instruments as long as their costs are known. And, as noted earlier, this is a conservative estimate, as other groups of the population also benefit from reduced noise levels but are not included in our calculations.

A glance at Figure 5 suggests that the population density is high close to the highways and freeways around the valley axis of Wuppertal (running from northeast to southwest). Assuming a density of 5,000 inhabitants per km^2 and 1% of the population being one school cohort, our estimates suggest to invest in noise abatement around the valley axis of Wuppertal, but possibly not to invest at the roads in the northwestern or southeastern part of the city, unless embankments are an option.

6. Conclusion and Discussion

Noise pollution is detrimental to health and to cognitive development of children. This is not only true for extreme level of noise, like noise from an airport, but also for traffic noise in a typical urban area. Using a census of preschool children of a city in Germany, this paper shows that children who are exposed to permanent traffic noise during the night fall significantly behind in terms of school readiness. Being exposed to 10 dB(A) additional noise eliminates the positive effect on school readiness of about 3 months in kindergarten. Moreover, the effect becomes stronger for children who are exposed to permanent noise levels higher than 50 dB(A) at night. We contribute to the literature and the policy debate by working with administrative data and focusing on the everyday exposure to noise instead of looking at case studies with exceptionally high levels of noise. Possible policy instruments are either publicly provided noise abatement, like soundwalls and quiet pavement, or legal rules like 30 km/h zones. In this paper, we assess the public cost of five different abatement instruments and compare them to the benefits. It turns out that abatement in densely populated urban areas of about 3,000 to 5,000 per km^2 can be cost efficient, even with a conservative assessment of the benefits.

Acknowledgments

We gratefully acknowledge support by several departments of the city of Wuppertal in particular for granting access to SEnMed, road traffic noise, suspension railway noise, and city block data. Data on railway noise by courtesy of the German Federal Railway Authority (Eisenbahn-Bundesamt).

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