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The association of road traffic noise with cognition in adolescents: A cohort study in Switzerland

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ABSTRACT

Environmental noise exposure has been shown to affect children's cognition, but the concept of cognition is multifaceted, and studies on associations with noise are still inconclusive and fragmented. We studied cognitive change within one year in 882 adolescents aged 10–17 years in response to road traffic noise exposure.

Participants filled in a comprehensive questionnaire and underwent cognitive testing twice at an interval of one year. Figural and verbal memory was measured with the Intelligenz-Struktur-Test (IST), and concentration accuracy and constancy were measured with FAKT-II and d2 test. Exposure to noise and other environmental stressors were modelled for school and home location at baseline. Missing data was addressed with multiple imputation. Cross-sectional multilevel analyses and longitudinal change score analyses were performed.

In cross-sectional analyses, figural memory was significantly reduced by −0.27 (95%CI -0.49,-0.04) units per 10 dB road traffic noise increase at home (L_{den}). Longitudinal analyses showed a significant reduction of concentration constancy Z-scores between baseline and follow-up by −0.13 (95%CI -0.25, 0.00) per 10 dB road traffic noise at home (L_{den}).

Our study indicates that road traffic noise at home reduces cognitive performance in adolescents. Larger cohorts with longer follow-up time are needed to confirm these results.

1. Introduction

Transportation noise has been linked to many negative outcomes affecting health, including noise annoyance, cardiovascular diseases and reduced sleep quality (Clark and Paunovic, 2018; EEA, 2020, Thompson et al., 2022). The European Environmental Agency (EEA) estimated that in 2017 in Europe about one million healthy life years were lost due to noise (EEA, 2020). Children are particularly vulnerable to the negative effects of noise exposure (WHO, 2009).

According to recent reviews, cognitive impairment in children was consistently associated with aircraft noise exposure, whereas the associations with road and railway noise were less clear (EEA, 2020, Thompson et al., 2022). The EEA estimated that in 2017, in Europe, due to aircraft noise, 75 DALYs in children were lost due to cognitive impairment and 12′400 children aged 7 to 17 were affected by aircraft noise induced reading impairment (Clark et al., 2006; van Kempen, 2008; EEA, 2020). In principle, the acute effect of noise on cognition can be studied in randomized controlled human experimental studies in laboratory settings. One study exposed pupils aged 11–13 and 14–16 years to different noise levels through headphones. They found a reduced cognitive performance in the over 70 dB condition for all, while only the older age group was affected negatively by a lower noise level of 64 dB (Connolly et al., 2019). To address effects of chronic noise exposure epidemiological studies on larger population samples are needed.

Scientific literature discusses two main pathways how chronic noise exposure may affect children's and adolescents' cognitive impairment: disruption of sleep and disruptions of learning processes by noise exposure (Basner et al., 2014; Stansfeld and Clark, 2015). These pathways may work differently at different stages of development. Good quality sleep is a requirement for healthy development of children and

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Abbreviations

Bedroom orientation	bedroom orientation towards or away from the loudest street passing the house
BL	baseline
EMF	cumulative brain dose of electromagnetic field
FU	follow-up
IQR	interquartile range
MI	Multiple Imputation

adolescents. Children go to bed earlier and sleep longer, therefore their exposure time windows include hours with relatively high traffic volumes. On the other hand, adolescents may go to bed later and their chronotype is shifted towards later awakening during the day (Fukuda and Ishihara, 2001). Thus, noise induced wakening in the morning may result in sleep deprivation of adolescents. Other pathways related to noise exposure at school are frustration of the teachers, resulting in lower quality teaching and disruption of communication through loud noise events, thus reducing productive teaching time. In general, noise pollution at home or at school may lead to learned helplessness (Evans and Stecker, 2004) resulting in resignation or demotivation, which may have a negative impact on learning capability. Other than sleep and learning disruption, the heightened levels of stress hormones affects mental health, which is associated with cognitive capacity, as well as

Table 1
Selection of noise exposure variables and covariates with cognitive outcomes at baseline.

	N	Verbal Memory	N	Figural memory	N	Total memory	N	Concentration accuracy	N	Concentration constancy
Mean (IQR for memory, SD for concentration)	783	4.8 (3,7)	772	7.7 (6,10)	769	12.5 (10,18)	584	0 (1)	584	0 (1)
L_{den} home road traffic (dB)										
<40	33	4.1	32	8.3	32	12.5	19	0.24	19	−0.09
40 - < 50	254	5.2	252	7.9	251	13.1	184	0.01	194	0.00
50 - < 55	203	4.7	201	7.6	201	12.3	149	0.01	149	−0.04
>55	293	4.7	287	7.5	285	12.3	222	−0.03	222	0.04
L_{night} home (dB(A))										
<30	24	4.1	23	8.2	23	12.5	16	0.36	16	−0.03
30 - < 40	188	4.9	187	8.0	186	12.9	146	0.01	146	−0.05
40 - < 45	246	5.0	243	7.8	243	12.7	177	0.00	177	−0.01
>45	325	4.7	319	7.5	317	12.2	245	- 0.02	245	0.05
L_{day} school (dB(A))										
<40	9	7.0	9	7.6	9	14.6	6	−0.32	6	0.04
40 - < 50	310	4.5	304	7.5	302	12.1	233	−0.11	233	−0.06
50 - < 55	242	4.9	239	7.8	239	12.6	167	0.20	167	0.17
>55	222	5.0	220	8.0	219	12.9	178	−0.01	178	−0.06
L_{den} home rail (dB)										
<30	432	4.9	426	7.8	423	12.8	303	0.00	303	−0.03
>30	351	4.7	346	7.6	346	12.3	281	0.01	281	0.04
Sex										
Female	436	5.2	432	8.2	430	13.3	339	0.01	339	0.01
Male	347	4.4	340	7.1	339	11.6	245	0.00	245	−0.01
Age										
<13	82	4.6	81	8.1	81	12.7	46	−0.37	46	−0.29
13 - < 14	337	5.0	332	7.7	330	12.8	240	−0.03	240	−0.05
14 - < 15	372	5.0	270	7.8	270	12.8	223	0.13	223	0.16
>15	92	3.9	89	6.8	88	10.7	75	−0.02	75	−0.09
bedroom orientation										
Missing	34	3.6	34	2.8	34	9.7	28	0.33	28	0.41
towards or side loudest street	281	5.0	274	7.6	274	12.6	212	−0.10	212	−0.07
away from loudest street	468	4.8	464	7.9	461	12.7	344	0.04	344	0.01
highest parents' education (lowest to highest)										
Missing	139	4.0	134	6.6	134	10.6	105	−0.11	105	−0.09
no education	5	3.4	6	5.5	5	8.8	5	0.61	5	0.35
mandatory school	18	3.3	18	7.2	18	10.5	15	−0.31	15	−0.19
training school (apprenticeship)	270	4.9	267	7.6	266	12.5	204	0.02	204	0.07
secondary school (gymnasium)	58	5.4	58	8.0	58	13.5	38	−0.03	38	−0.20
college of higher education (applied university)	230	5.1	226	8.2	225	13.4	170	0.04	170	0.01
University	63	5.4	63	8.5	63	14.0	47	0.15	47	0.11
school level of participants (lowest to highest)										
Secondary school C	138	3.3	136	6.2	135	9.5	106	−0.09	106	−0.16
Secondary school B	228	4.4	224	7.3	224	11.6	174	0.00	174	−0.10
Secondary school A	247	5.3	243	8.1	242	13.4	194	0.06	194	0.09
gymnasium	170	6.1	169	8.9	168	15.0	110	0.01	110	0.16
nationality of parents										
both Swiss	606	5.0	598	7.7	596	12.7	449	−0.01	449	−0.04
Swiss and other	107	4.8	104	8.2	104	13.0	75	0.11	75	0.28
both other	70	3.7	70	6.7	69	10.5	60	−0.05	60	−0.03

Note: L_{den} (00:00–24:00), with a 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00).
Variable bedroom orientation reflects follow-up data, due to its use in cross-sectional and longitudinal analyses.
IQR: Interquartile range; SD: Standard Deviation; table represents data before imputation.

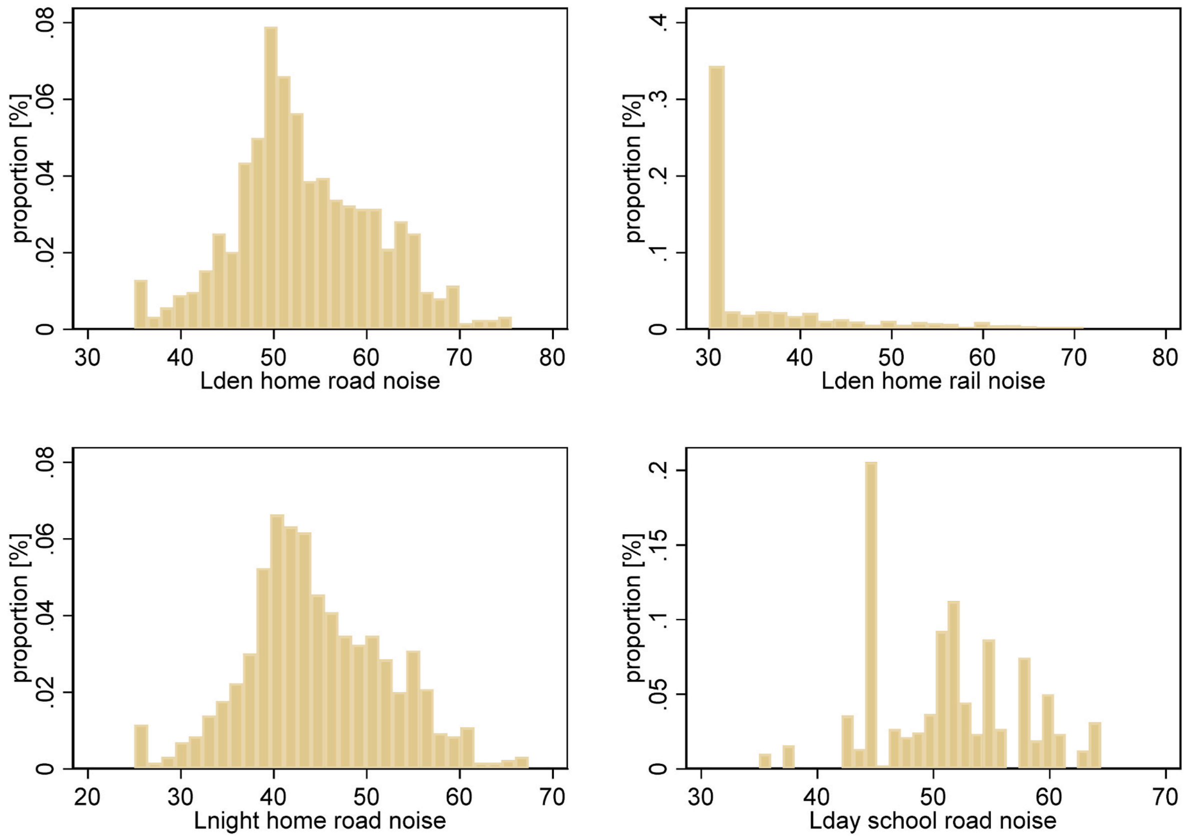

Fig. 1. Distribution of noise exposure metrics at home and at school. Note: L_{den} (00:00–24:00), with a 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00).

biological responses, such as inflammation and oxidative stress (Lupien et al., 2007; Daiber et al., 2020).

Cognition is multifaceted. Thus, estimating the overall effect of noise on cognition is not straightforward. Noise research on children and in few cases adolescents has evaluated a range of possible outcomes, including academic performance, reading, verbal and language ability, attention, executive function and memory (Stansfeld et al., 2010; Van Kempen et al., 2010; Clark et al., 2012; Papanikolaou et al., 2015; Klatte et al., 2017; Thompson et al., 2022). Further complexity is added by the fact that there is a variety of ways to measure each domain.

Attention is a state of focusing on one thing, while tuning out other stimuli. Concentration, for example, describes sustained attention over a period of time or until a task is done. The review on cognition and noise by Thompson et al. (2022) identified six studies in children and adolescents on attention and road traffic noise that they considered to be an "equal mix of supportive and unsupportive literature". For aircraft noise they noted that ten identified papers slightly supported an association with lower attention.

In terms of memory capacity and road traffic noise Thompson et al. (2022) concluded that available literature is unsupportive of a causal link, since two studies showed improvements in cognition with increasing noise and the remaining three studies did not show an association. For aircraft noise, however, they identified 12 studies, which they considered "mostly supportive" for negative consequences.

The current body of evidence is mixed, and depends on the specific cognitive domain and the exposure setting (i.e. home vs. school). Still, only a few studies have addressed the effects of road traffic noise exposure at home, although road noise is the dominant noise exposure source especially in urban environments. Further, knowledge is limited by the fact that most existing studies on cognition and noise have a cross-sectional design, which is less suited to evaluate causality than longitudinal studies. Many of the studies were done using aircraft noise exposure only, which represents a very specific, loud and intermittent type of noise, and many studies have focussed on noise exposure data collected at schools (Thompson et al., 2022). Thus, there is a need for studies that evaluate both, road traffic noise exposure at home and at school, to allow the exploration of both pathways through sleep and direct effects of noise on the learning process. Finally, children are the most studied school aged group, and more knowledge is needed specifically on how adolescents are affected by noise (Clark and Paunovic, 2018).

The aim of this research was to study how cognitive functions of adolescents are affected by road traffic noise exposure in their homes and at school. The cognitive functions in question are memory (figural and verbal) and attention (concentration accuracy and constancy). We hypothesized that long-term road traffic noise exposure is associated with lower overall memory and concentration capacity in cross-sectional analyses. Further, we hypothesized that a longitudinal analysis would reveal a decline of memory and concentration after one year follow-up for participants who were exposed to increased noise pollution at school and/or at home, in particular if they slept towards the loudest street.

2. Methods

2.1. Sampling and design

This study uses the HERMES (Health effects related to mobile phone use in adolescents) cohort, which had originally been set-up to measure the impact of radiofrequency electromagnetic fields due to cell phone use on behaviour, cognition and quality of life of adolescents (Schoeni et al., 2015; Roser et al., 2016; Foerster et al., 2019). The data collection took place in central Switzerland and Basel in two consecutive waves, each using a different cohort of participants. Both cohorts underwent the

Table 2
Cross-sectional analyses: Associations of modelled road noise at home (L_{den}) per 10 dB and sleeping towards street (for model 3) with various cognitive outcomes using multilevel models, clustered by id.

	N		Model 1[a]	Model 2[b]	Model 3[c]
	Individuals	observations	Difference (95% CI)		
Verbal memory					
Road noise (10 dB)	845	1522	−0.08 (−0.29, 0.13)	0.18 (−0.02, 0.38)	0.19 (−0.02, 0.39)
Sleeping towards street					−0.02 (−0.31, 0.27)
Figural memory					
Road noise (10 dB)	844	1515	**−0.48 (-0.71, -0.24)**	**−0.27 (-0.49, -0.04)**	**−0.26 (-0.49, -0.03)**
Sleeping towards street					−0.03 (−0.35, 0.28)
Total memory					
Road noise (10 dB)	843	1508	**−0.57 (-0.94, -0.19)**	−0.09 (−0.43, 0.25)	−0.08 (−0.43, 0.27)
Sleeping towards street					−0.07 (−0.54, 0.41)
Concentration accuracy					
Road noise (10 dB)	788	1253	−0.08 (−0.16, 0.01)	−0.04 (−0.13, 0.04)	−0.04 (−0.13, 0.05)
Sleeping towards street					−0.04 (−0.15, 0.08)
Concentration constancy					
Road noise (10 dB)	788	1253	−0.02 (−0.11, 0.06)	0.00 (−0.09, 0.08)	0.00 (−0.09, 0.09)
Sleeping towards street					0.00 (−0.12, 0.11)

Note: L_{den} (00:00–24:00), with a 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); PM_{10}: particular matter 10 μm and smaller; NDVI: normalized difference vegetation index; EMF: cumulative electromagnetic field brain dose (see (Roser et al., 2015) for dosimetric model).

[a] Model 1 adjusted for sex and age.

[b] Model 2 adjusted for sex, age, drinking any alcohol, smoking, parents' education, nationality, school level, physical activity, screen time, $PM_{10,}$ NDVI, EMF.

[c] Model 3 adjusted as model 2 + bedroom orientation towards loudest street by house.

same data collection and cognitive measurements (1. cohort: Baseline (abbr.: BL): 2012/13; Follow-up (abbr.: FU): 2013/2014 and 2. cohort: BL: 2014/15; FU: 2015/16). In the first cohort, 442 students participated and in the second 457. For the analyses, these were combined into a single cohort of 899 participants.

The recruitment process started with the researchers contacting directors of public secondary schools of all levels in Switzerland. The "school level" refers to the difficulty level of schools, with four types that range from lowest to highest difficulty: Secondary school C, B, A and "Gymnasium". If participation was agreed by the director and respective class-teachers, the researchers visited the class, informed the students about the study, and handed out study information material plus consent forms for both parents and students. Students who decided to participate filled in questionnaires and completed cognitive testing at BL and FU during school hours. Their parents filled in questionnaires at BL and FU, which were returned by post to the researchers. All participants filled in an informed consent form.

2.2. Outcome

The main outcome variables were the cognitive functions memory and concentration administered by computerized tests. For memory, we used part of the Intelligenz-Struktur-Test (IST) (Liepmann, 2007) that measures figural (score range: 0–11) and verbal memory (score range: 0–13) with a potential maximum memory score of 24. Verbal memory was measured by presenting the participants with five sets of two to five words grouped by category (e.g. category "cities": Rome, Amsterdam, New York, Madrid) for 1 min each. The participants were next presented with a letter and asked to recall the memorized word starting with said letter as well as its category. This was done 11 times. For figural memory, participants memorized 13 pairs of abstract symbols for 1 min each. Immediately following, participants had to pair 13 presented symbols with their counterpart from a choice of five options. The recall phase of both the figural and the verbal test each lasted 2 min.

Concentration was measured in constancy and accuracy with either the FAKT–II–test (Moosbrugger and Goldhammer, 2007), or the d2-test (Brickenkamp, 1962). Both tests are discrimination tasks in which participants had to discern between target and non-target items. Constancy is measured through the variance of time passed between how long an item appeared before a decision (target or non-target item) is taken. Higher constancy describes a more uniform working pattern. Accuracy describes the relative correctness of the answers given as a fraction of 100%. During the second wave of data collection, software problems with the FAKT-II test resulted in missing data. The test was thus changed mid-wave to the d2-test. For the combined cohort (N = 899), this resulted in a mix of tests at both BL (72.3% with FAKT-II, 27.7% with d2) and FU (42.9% with FAKT-II, 53.1% with d2). Given the different outcome ranges of the two tests, the results were Z-standardized to be comparable (mean = 0, SD = 1).

All outcome variables were retained as continuous to keep as much information as possible. In all variables, higher scores mean better cognitive function. For the longitudinal analyses, the BL score was subtracted from the FU score. Therefore, a negative number represents a reduction in cognitive function and a positive indicated heightened cognitive function after one year.

2.3. Noise exposure

We modelled noise from road traffic, railway, aircraft and total noise (all three sources combined) within the SiRENE project (Karipidis et al., 2014; Héritier et al., 2017). As road traffic noise was the most dominant exposure in our cohort we consequently focused on that, and used the other three exposures only in secondary analyses. The aircraft noise variable was only used as part of the total noise variable. In SiRENE road traffic noise was computed for the year 2011 using the model StL-86, and railway noise was computed using the Swiss railway noise model SEMIBEL for each building in Switzerland (BAFU, 2009). Aircraft noise was calculated for the three Swiss airports Basel, Geneva and Zurich, as well as for the military airfield in Payerne (Krebs et al., 2004; Empa, 2010). For the civil airports, aircraft noise was calculated using air traffic and radar data, with acoustic footprints per aircraft type and air route. For the military airfield, noise was calculated using aircraft types, number of flights, idealized flight trajectories, as well as operation times.

We extracted several noise metrics. L_{night} is the equivalent noise exposure in decibels during night hours. L_{den} is a metric reflecting 24 h noise, that penalizes noise in the evening (18:00–23:00 h) with 5 dB and night (23:00–07:00 h) with 10 dB to reflect more severe health outcomes by noise during those times. Calculation results were used for the loudest façade point of every house or school address at the level of the floor of the participant or, if not known, the first floor.

For 20 participants who moved homes between survey times, a time-weighted average was calculated according to the moving date. Fifty participants lived in buildings built later than the date of the SiRENE

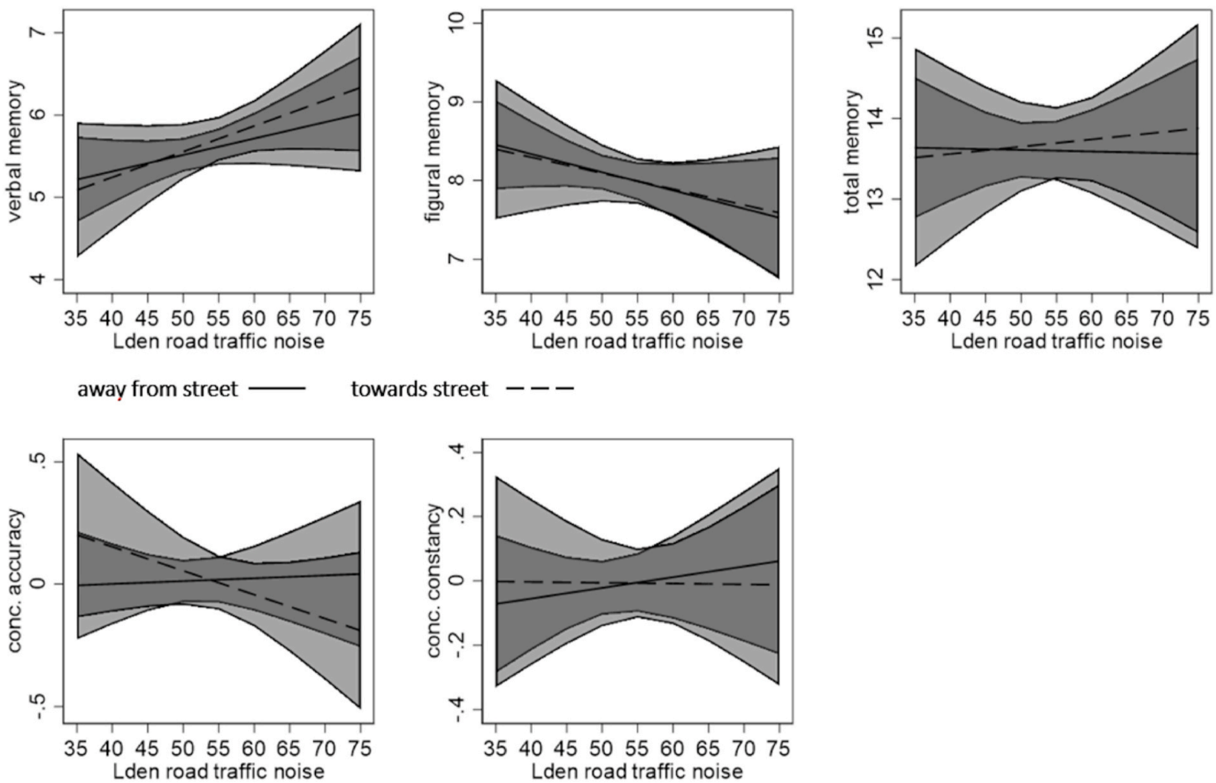

Fig. 2. Cross-sectional analyses: Associations of modelled road traffic noise in L_{den} at home and cognitive outcomes stratified by orientation to the street, using multilevel models, clustered by id for complete case analysis*
* we excluded the screen time variable for its large proportion of missing values.

noise model. These were identified based on a distance of more than 20 m between the geocoded address (new building) and the noise database address (old building with modelled noise exposure). We used building data by the Federal Office of Topography swisstopo (map.geo.admin.ch) to visually inspect the situation and corrected exposure manually. We added (or subtracted) 3 dB per doubling (or halving) of the distance from street to location of the modelled noise compared to the new buildings (actual location of participants home) location.

We used censoring of lower range exposure variables to account for possible audible background noise (Héritier et al., 2017; Vienneau et al., 2019). Any noise exposures below the following thresholds were changed to the censoring values: 35 dB (road and total noise), 30 dB (railway and aircraft noise) and 25 dB (all noise sources at night).

2.4. Covariates

The highest achieved education by parents was included as a covariate (no education, mandatory education, training school (apprenticeship), secondary school “gymnasium”, applied university, university), as was the parents’ nationality (i.e. 2, 1 or 0 parents of Swiss nationality). Explanatory variables for the participants included: age (continuous), sex (m/f), school level (ranging from lowest to highest difficulty level: Secondary school C, B, A, and Gymnasium), alcohol consumption (yes/no), smoking (yes/no), physical activity (1–3x/month, 1x/week, 2–3x/week, 4–6 x/week, daily), screen time (continuous in minutes) and cumulative electromagnetic field brain dose (abbr.: EMF; in mJ/kg). As the main noise exposure always reflected the noisiest point on the façade of the floor of the participant (or, if not know, the first floor of the building), the information whether the bedroom of the participant was located towards or away from the loudest street passing the house (abbr.: *bedroom orientation*; towards street/away from street) was also collected. As a proxy for puberty development between baseline and follow-up, difference in height between BL and FU (cm) was used in the longitudinal analyses. The dosimetric model for the EMF variable was developed in an earlier HERMES-study (Roser et al., 2015). It was included as an explanatory variable as it had shown to be associated with cognitive variables in the previous HERMES-studies.

For air pollution, 200 m × 200 m grids of annual mean NO_2 and PM_{10} were available (Meteotest, 2017). PM_{10} was chosen as the marker for air pollution. The value from the grid square in which the participant’s home was located was extracted for each year. Using an NDVI map of Switzerland from Vienneau et al. (2017), a 500 m buffer was calculated to reflect greenness in the neighbourhood.

2.5. Data analyses

2.5.1. Primary analyses

We used two main analysis designs looking at the linear association between noise and cognitive functions: A cross-sectional multilevel design and a longitudinal change score design. The cross-sectional analyses were conducted using all observations of study participants in linear random intercept multilevel models with participant as the cluster variable. This corrects for the within subject correlation of repeated data. For the longitudinal analyses, the outcome variable was BL cognition score subtracted from the FU score. This means, that negative values equal to a reduction in cognitive functions at FU. In both analyses, we adjusted for the same variables (Model 1: adjusted for sex and age; Model 2: all mentioned covariates in section 2.4) and an added proxy for puberty (change in height over a year) in the longitudinal analyses. Bedroom orientation was only used in Model 3 in cross-sectional and longitudinal analyses and in the interaction analyses. The interaction analyses, run on both the cross-sectional and longitudinal analyses using the adjusted Model (M3), included an interaction term between the continuous road traffic noise exposure and the binary bedroom orientation variable.

Table 3
Longitudinal analyses: Associations of modelled noise at home (L_{den}) per 10 dB and sleeping towards street (for model 3) with change in cognitive scores between baseline and follow-up.

	N	Model 1[a]	Model 2[b]	Model 3[c]
		Difference (95% CI)		
Verbal memory				
Road noise (10 dB)	677	0.00 (−0.29, 0.29)	0.01 (−0.30, 0.32)	0.06 (−0.26, 0.39)
Sleeping towards street				−0.30 (−0.80, 0.21)
Figural memory				
Road noise (10 dB)	671	−0.18 (−0.50, 0.13)	−0.08 (−0.41, 0.25)	−0.10 (−0.45, 0.24)
Sleeping towards street				0.11 (−0.43, 0.65)
Total memory				
Road noise (10 dB)	665	−0.19 (−0.66, 0.27)	−0.09 (−0.58, 0.41)	−0.04 (−0.56, 0.48)
Sleeping towards street				−0.23 (−1.04, 0.57)
Concentration accuracy				
Road noise (10 dB)	465	−0.01 (−0.13, 0.11)	0.02 (−0.11, 0.14)	0.01 (−0.12, 0.13)
Sleeping towards street				0.06 (−0.13, 0.25)
Concentration constancy				
Road noise (10 dB)	465	**−0.14 (-0.26, -0.02)**	**−0.13 (-0.25, 0.00)**	**−0.13 (-0.26.0.00)**
Sleeping towards street				0.02 (−0.18, 0.22)

Note: L_{den} (00:00–24:00), with a 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); PM_{10}: particular matter 10 μm and smaller; NDVI: normalized difference vegetation index; EMF: cumulative electromagnetic field brain dose (see (Roser et al., 2015) for dosimetric model).

[a] Model 1 adjusted for sex and age.

[b] Model 2 adjusted for sex, age, drinking any alcohol, smoking, parents' education, nationality, school level, physical activity, screen time, PM_{10}, NDVI, EMF, difference in height.

[c] Model 3 adjusted as Model 2 + bedroom orientation towards loudest street by house.

2.5.2. *Secondary analyses*

Secondary analyses involved additionally adjusting Model 2 for the L_{day} at school. Analyses were also done by using a different main exposure in Model 2: L_{night} road at home, L_{den} total at home, L_{day} road school, L_{den} railway at home.

2.6. *Missing data and multiple imputation*

We addressed any missing variables in the questionnaires with multiple imputation (MI). The MI-method allows creating multiple plausible completely imputed datasets, which are first individually analysed, and their outcomes then consolidated into one result. By creating several different datasets, this method allows for uncertainty estimation in the imputed value, while not ignoring incomplete observations in the analyses and therefore excluding information that might lead to bias. We created 20 fully imputed data sets using MICE (Multiple Imputation by Chained Equation) to impute missing predictors and outcome variables (Kontopantelis et al., 2017). The following complete variables were used to inform the imputation process: L_{den} road traffic noise, school level of adolescent, nationality of parents, urban/rural residence, PM_{10}, NDVI, age at BL and sex. In addition, the following variables with missing values were used in the imputation process: parents education (once measured = 167), height (BL = 15, FU = 53), weight (BL = 42, FU = 70), alcohol consumption (BL = 31, FU = 63), smoking (BL = 6, FU = 52), physical activity (BL = 4, FU = 48), screen time (BL = 245, FU = 139), EMF (once measured = 47) and bedroom orientation (BL = 8, FU = 48), verbal memory (BL = 105 (12%), FU = 149 (17%)), figural memory (BL = 116 (13%), FU = 145 (16%)) total memory score (BL = 119 (13%), FU = 149 (17%)) concentration accuracy (BL = 304 (34%), FU = 219 (25%)), concentration constancy score (BL = 304 (34%), FU = 219 (25%)).

For all analyses, except the sensitivity analyses, we excluded observations that had missing outcome in the original data. We conducted sensitivity analyses for this method of analysing MI data by comparing our results for primary analysis by also running them using the fully imputed dataset, including observations with imputed outcome data.

Significance level was set to 5%. All analyses were run with Stata 15.1, the figures were created in Stata or R Version 4.1.1.

3. Results

3.1. *Descriptives*

In wave 1, 19% of contacted schools participated, while 37% of informed students participated (n = 442). In wave 2, participation rate of schools was not assessed, but 56% of contacted students (N = 457) participated. In wave 1, students were recruited from 23 schools, in wave 2, students were recruited from 22 schools. Two schools were used in both waves. Of 899 students who agreed to participate at BL, eleven were excluded from the analyses because of incorrect addresses (n = 4), or missing questionnaires (n = 7). Of the resulting 888 BL participants, 46 did not participate in the FU, which was on average 376 days later. Of the drop-outs, 22 were male and 24 female.

At BL and prior to imputation, participants were on average 14 years old, 56% were female, and most had two Swiss parents (76%) (Table 1). The mean memory outcomes were 4.8 (IQR: 3, 7) for verbal memory, 7.7 (IQR: 6, 10) for figural memory, and 12.5 (IQR: 10, 18) for total memory. Distribution of the cognitive outcomes are shown in Suppl. Figure 1. Table 1 depicts the outcome scores at baseline in relation to various covariates such as age, sex and school level. Figural memory and concentration accuracy decreases with increasing noise exposure.

Mean road traffic exposure L_{den} was 52 dB with an interquartile range (abbr. IQR) between: 49 and 59 dB (Fig. 1). Mean L_{night} road traffic noise at home was 44 dB(A) (IQR: 40, 50 dB(A)). Only a few participants experienced railway noise exposure above the censored L_{den} value of 30 dB (median 30 dB (IQR: 30, 40 dB)). The L_{day} school noise exposure showed a spike at around 46 dB (median: 53 dB (IQR: 47, 57 dB)). This spike represents many adolescents attending the same school and therefore experiencing the same exposure.

Differences in exposure by covariate groups were noted for nationality of parents (higher road traffic noise exposure L_{den} for those with foreign nationality parent(s): 53 dB, 55 dB and 57 dB for 2, 1 and 0 Swiss parents, respectively), bedroom orientation (56 dB and 51 dB L_{den} for towards a street and on a quiet side, respectively), and school level of participants (56 dB and 53 dB for lowest and highest level, respectively) (Table S1).

3.2. *Primary analyses*

3.2.1. *Cross-sectional analyses of transportation noise with cognitive outcomes*

In Model 1 (minimally adjusted for age and sex), the cross-sectional analyses showed a significant reduction of figural memory by −0.48 (95%CI -0.71,-0.24) on the 12-point scale per 10 dB road traffic noise increase at home (L_{den}) (Table 2). In the fully adjusted Model 2, the association was less pronounced, but stayed significant at −0.27 (95%CI -0.49, −0.04) per 10 dB exposure. Verbal Memory showed no noteworthy association with noise exposure in the basic adjusted model, but after adjustments the relationship was tending towards a positive association (participants with more noise exposure seemed to have better verbal memory). No other associations with other outcomes were found. Adding bedroom orientation to the adjustments (Model 3) did not change the relationship between modelled noise and any outcome.

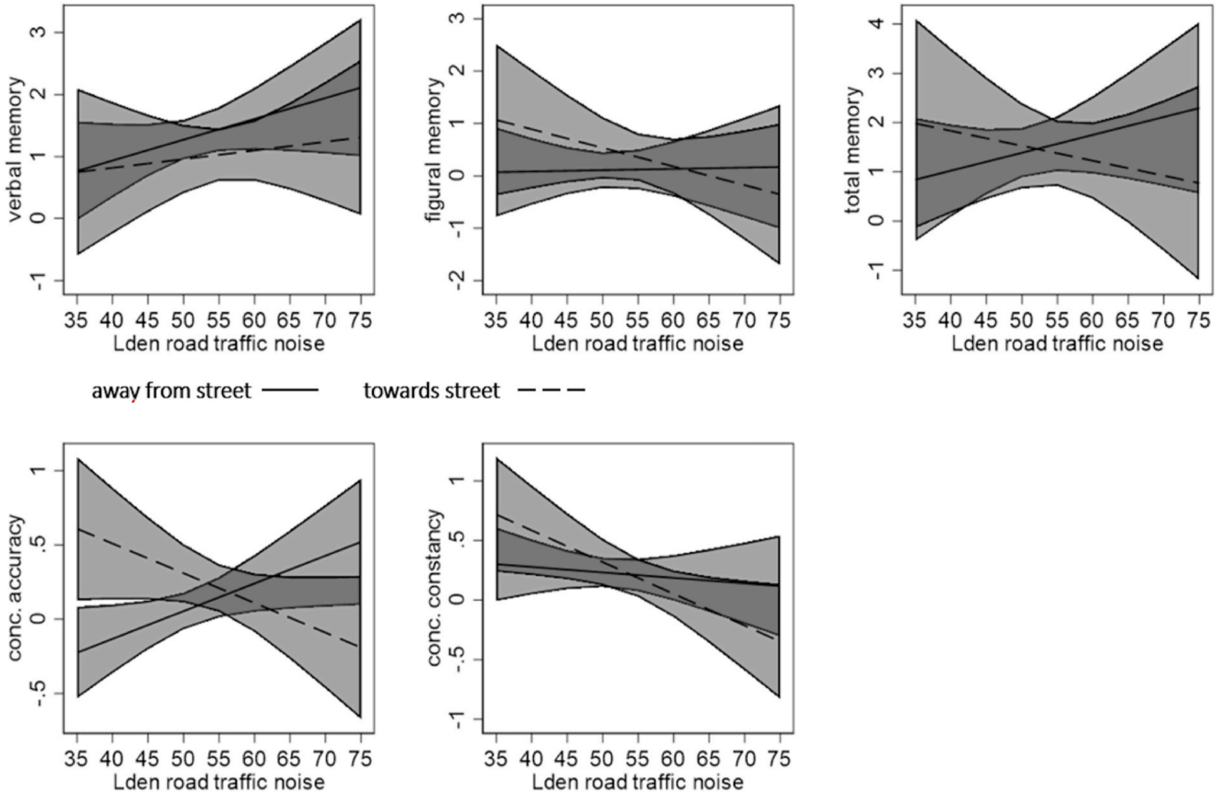

Fig. 3. Longitudinal analyses and interactions: Associations between road traffic noise in L_{den} at home and change of cognitive outcomes within a year stratified by bedroom orientation for complete case analysis*

* we excluded the screen time variable for its large proportion of missing values.

Bedroom orientation was not significantly associated with any outcome variable in Model 3.

Fig. 2 shows the predicted results of Model 2 (excl. screen time due to its large amounts of missing observations) stratified by bedroom orientation. Only for the outcome concentration accuracy, the regression lines indicated participants sleeping in a bedroom facing the loudest street had lower concentration accuracy when exposed to higher road traffic noise than people sleeping away from the loudest street. The results for the interaction analysis with the same data and model as in our primary analysis can be seen in Supplement Table S2. We can see the significant, but small interaction between road noise and bedroom orientation for cognition accuracy.

3.2.2. Longitudinal analyses of traffic noise with change in cognitive outcomes after a year

In fully adjusted models, the difference in concentration constancy Z-score between BL and FU was significantly lower by −0.13 (95%CI -0.25, 0.00) per 10 dB road traffic noise increase at home (L_{den}) (Table 3). None of the other outcomes showed associations between noise exposure and the change in cognitive functions after a year. Those sleeping towards the loudest street experienced a negative impact of higher noise exposure after one year (Fig. 3). This is most pronounced for concentration accuracy, but also apparent for concentration consistency, figural memory and total memory. The interaction model using the same data as in the primary analysis (Table 3) is shown in the Supplement Table S3. Significant interactions between road traffic noise and bedroom orientation appear for the outcomes cognition accuracy and cognition constancy.

3.3. Secondary analyses

Adding road traffic L_{day} at school neither showed an independent association with any cognitive outcome in Model 2, nor changed the original effect estimate of L_{den} road traffic at home on noise (Supplement Table S4). No other significant associations were found for other exposures (L_{day} road at school, L_{den} rail at home) except for L_{day} road traffic noise at home, which showed similar associations with the outcomes as L_{den} road at home (Supplement Tables S5 and S6).

3.4. Sensitivity analyses

The Supplement Tables S7 and S8 show that sensitivity analyses based on imputed outcome data yields similar results as the main analyses (Model 2), where observations with missing outcome data were not considered.

4. Discussion

4.1. Summary of findings

In cross-sectional analyses we found that road traffic noise exposure at the most exposed façade was related to significantly lower figural memory. This finding was not confirmed in the longitudinal analysis with one-year FU, while, high road traffic noise exposure throughout one year was associated with a significant reduction in concentration constancy within that year. Strikingly, in longitudinal analyses negative consequences of noise were observed for four out of five outcomes in adolescents sleeping towards the loudest street by their house.

4.2. Bedroom orientation

This finding is consistent with a recent study by Brink et al. (2019) who showed a modifying effect of the bedroom orientation on the relationship between transportation noise and self-reported sleep disturbance. In our study, adolescents sleeping away from the noisiest street might be little noise exposed during sleep and the threshold to trigger sleep effects may not be reached. This effect might have been strengthened in our study as we saw higher overall modelled noise exposure for people sleeping towards the street. We do not have information on where adolescents spend most of their time. However, we assume that they study and sleep in their bedroom and therefore the exposure at their bedroom window is well suited to also characterize potential disturbance during homework. It is thus plausible that noise exposure levels in their bedroom are most critical, whereas noise exposure at the most exposed façade rather concerns other activities than learning such as social activities within the household.

4.3. Comparing to the literature

As discussed in the 2018 WHO review on noise and cognition, the variety of cognitive outcomes used in the different studies makes it especially difficult to compare results with those of previous research (Clark and Paunovic, 2018). For example, one study found a significant association between aircraft noise at school and recognition memory (Clark et al., 2012) in children aged 9–10 years. The measured effect size was a decrease of −0.35 (95%CI: −0.61, −0.09) recognized items per increase of 10 dB L_{den}. The score ranged from 15 to 30 units. Our figural memory score ranges from 0 to 11 and showed a significant cross-sectional association of −0.27 (95%CI: 0.49, −0.04) less memorized items per 10 dB increase in road traffic noise L_{den}. Though related, these outcomes, their measures and ranges make them difficult to combine and to derive generalizable statements. In our study, we used data from a study designed to study effects of electromagnetic field exposure and did not streamline cognitive testing with existing noise studies. The fact that memory shows associations in our cross-sectional analysis and concentration constancy changes over the duration of a year, could indicate different timelines of effect. Figural memory could be a longer acquired negative association with noise, while concentration constancy was affected by noise within a year.

Assessing the relevance of our findings, we compared the effect sizes of the cross-sectional and longitudinal analyses with differences between school levels. Per 10 dB L_{den} road noise increase, figural memory decreases by 0.26 units, whereas we observed about 0.8 unit difference per increase in school level (e.g. from level B to A or from A to gymnasium) (Table 1). Concentration constancy Z-score decreases by 0.13 (mean = 0, SD = 1) per 10 dB within a year of L_{den} road traffic noise exposure, which is about the same as the difference per school level. Other coefficients of associations were lower and not significant.

Contrary to other studies (Van Kempen et al., 2010), we found no associations for road traffic noise at schools with concentration or memory. This finding might have been impacted by following aspects: Since we modelled highest façade exposure per school building, we may have introduced substantial exposure misclassification for large school areas consisting of several buildings. This type of exposure misclassification is expected to be less relevant in previous studies on aircraft noise. Further, high-school students have more complex curriculums, which in turn lead to more movement throughout the school buildings and there would not have been one predesignated room for measurements. Added to that, the social noise in classrooms likely mostly overpowered (estimated 64 dB(A) (Shield et al., 2015)) our main source of noise, outdoor traffic noise (mean noise: 52 dB L_{den}). Further, schools experiencing high levels of road traffic noise would most likely feature windows with double or triple glazing.

To the best of our knowledge, most studies on noise and cognition show associations with aircraft noise and none of the previous studies found road traffic noise exposure at *home* to be associated with attention/concentration or memory. Therefore, our study is the first to show associations for these specific cognitive variables with road traffic noise at home. Also, the fact that we found a significant association between road traffic noise at home and concentration constancy change within only one year indicates a relevant relationship. This one-year change in adolescents also suggests that effects of noise may still happen at the later stages of development.

Of note, in the cross-sectional analyses we found a non-significant trend towards higher verbal memory with increased road traffic noise exposure at home. This is most likely a chance finding, although two previous papers also reported a positive association of road traffic noise at school with increased memory performance. However, these studies looked at episodic and information recall memory (Stansfeld et al., 2005; Matheson et al., 2010). A somewhat speculative interpretation for our finding could be that by living in and adapting to noisier areas, adolescents learn to focus more to understand speech, thus developing verbal memory skills.

4.4. Strengths and limitations

One of the main strengths of this study is the longitudinal study design, which allowed us to measure potential changes in cognitive functions in relation to noise exposure over time. Being able to use both a cross-sectional and longitudinal approach allowed us to research two different aspects: since there is little change of noise exposure over time, the cross-sectional analysis may capture long-term effects of noise exposure, although this design comes with limitations in terms of causal interpretation. Longitudinal analyses are more robust in terms of causal inference and informative whether continued noise exposure still affects cognitive performance or whether a steady-state situation is reached at some point. Adolescents who have lived at a specific home for a good duration of their life might have already suffered the negative effects and plateaued, therefore not showing any further change through noise in our longitudinal design. Alternatively, the length of FU might have been too short to show significant changes of cognitive function in relation to noise.

The noise data gave us precise estimations of noise exposure for location and by noise source, while the inclusion of the variable bedroom orientation into the models as a proxy for bedroom noise exposure further improved that precision. Another strength of the study was the availability of both school and home noise exposure, which make up the majority of the participant's daily noise exposure, although noise modelling of schools is subject to higher exposure misclassification than residential modelling. Also, the availability of rich covariate information such as proxies for socioeconomic status like parental education level is expected to minimize potential confounding (Stansfeld and Clark, 2015).

Loss to follow-up is minimal in this cohort. Using multiple imputation in this study allowed us to include data from individuals that were missing just one or few of the covariate observations. This was most important for parental education (missed 167 observations), since this was asked in a separate questionnaire targeted to the parents. To address possible different results between two commonly used MI methods (imputing all data in MI process, then deleting observations with imputed outcome data for the main analysis and keeping all observations including those with imputed outcomes) we used the former approach as main analysis and the latter one as sensitivity analyses. The two methods produced similar results with respect to point and interval estimates.

The relative large amount of missing data for both concentration outcomes (before the test was changed from FAKT-II to d2), mostly due to software malfunctions, influenced the power of this study, but likely did not bias the results as they can be considered to be missing completely at random.

Thus, a larger cohort might have resulted in more precise estimates.

4.5. Conclusion and outlook

We found some indications of small associations between road noise at home and cognitive functions in adolescents, in particular if restricted to adolescents whose bedroom window faced to a major road. This is the first study to show these cognitive associations with road noise at home. One of two memory outcomes –figural memory – was associated with noise in cross-sectional analyses, indicating a potentially long-term effects, while one of two concentration outcomes – concentration constancy – was associated with higher noise exposure during a year. This may indicate a relatively short-term change in concentration constancy within only one year from noise exposure. To consolidate and specify findings in the future, longer follow-up time, standardisation in outcomes and larger cohorts would help to measure and specify effects.

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Declarations

The HERMES study was approved by the Ethics Committees of the Northwest – and Central Switzerland on June 08, 2018 (Project-ID, 2018–00980).

Authors' contributions

LT, MR: study concept and study design; LT, DV: data preparation; JH: statistical advise; LT: statistical modelling, write and revise manuscript; all: data interpretation, review and comment on manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.115031.

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