An epidemiological cohort study of adolescents:

Investigating behavioural problems and cognitive functions in relation to traffic noise exposure in Switzerland

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“Es gibt vielerlei Lärm, aber es gibt nur eine Stille.”
(“There are many kinds of noise, but only one silence.”)

Kurt Tucholsky

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List of abbreviations

Bedroom orientation: bedroom orientation towards loudest street by the house

BL: Baseline

EMF: cumulative brain dose of electromagnetic field

FU: Follow-up

Table S.: Supplement table

IQR: interquartile range

MI: Multiple Imputation

N_{Evt}: Number of events

IR: Intermittency Ratio

0 Summary

0.1. Background

Environmental noise is a widespread source of discomfort in everyday life and is an increasing topic of concern for both politicians and the general population. After particulate air pollution, noise exposure is the second highest contributor to the burden of disease of environmental exposures (Hänninen et al., 2014) and the WHO considers children to be at particular risk of the negative consequences of noise (WHO, 2009).

0.2. Aim and Objectives

The primary aim of this dissertation is to study how chronic exposure to environmental noise affects adolescent health. The aim was split in four objectives.

1. Analyse the association between transportation noise and adolescent cognitive functions and behaviour problems

2. Describe and quantify the role of transportation noise at home, at school and their relationship

3. Evaluate the role of different noise characteristics in impacting health outcomes

4. Use parameters that modify transportation noise reaching the participants, such as bedroom orientation towards the loudest side of the house, and determine their role in noise exposure.

0.3. Methods

All objectives were addressed with two studies that were based on following cohort and methodological approach:

The study cohort consisted of 899 Swiss adolescents aged 10-17 years, from whom data were collected twice with a one-year follow-up through questionnaires and cognitive testing. The study design was cross-sectional and longitudinal; the statistical models were adjusted for relevant confounders and explanatory variables. Outcomes of interest were behaviour problems measured with the strength and difficulties questionnaire (SDQ) and two cognitive functions: memory and concentration. As the only meaningful noise exposure in this particular cohort was road traffic noise (very few participants lived near other sources of transportation noise), this thesis' focus is road traffic noise exposure as a main exposure. The primary noise metric used throughout the study was the day-evening-night equivalent noise level (L_{den}). Analyses were conducted for both home and school locations, as well as for combinations of both. Additional analyses were conducted with other noise sources (railway noise, total noise (combination of road, rail and aircraft noise)) and other

noise metrics (noise levels at day and night (L_{day}, L_{night}), as well as Number of noise events (N_{evt}) and the Intermittency Ratio (IR) (Wunderli et al., 2016)). The variable bedroom orientation was used in interaction analyses and sensitivity analyses. Missing data was imputed using the multiple imputation technique (Sterne et al., 2009a).

0.4 Results

Both studies show small, but significant associations between environmental noise exposure and both cognitive functions and behavioural outcomes in a Swiss adolescent population.

Behavioural outcomes: In cross-sectional analyses, peer relationship problems were associated with higher levels of road noise at home. Changes in peer relationship problems within a year were not related with higher noise.

Cognitive functions: Worse figural memory was associated with higher noise exposure in cross-sectional analyses, while high road noise exposure at home for a year was associated with a lower concentration constancy. Strikingly, in longitudinal analyses, negative consequences of noise on cognitive functions were mostly observed in adolescents sleeping in bedroom facing towards the loudest street by their house.

Associations were found for road traffic at home, but not at school. Associations were only found for the equivalent sound metrics, not the N_{evt} and IR.

0.5 Discussion and Conclusion

These studies add to the knowledge of road traffic noises association between behaviour and cognition and are the first to show associations for cognition with road traffic noise at home. The fact that a significant association was found between road traffic noise at home with change in concentration constancy within only one year, indicates a potentially strong relationship. This one-year change in adolescents suggests that effects of noise may still happen at the later stages of development. Associations between road noise at school were not found for any outcomes. Following reasons are discussed: either due to misclassifications, no relevant road noise reaching the inside of the building or no existing association.

1. Introduction and background

1.1. Problem scope

Traffic-related noise pollution is a widespread phenomenon and has been shown to have negative effects on health and well-being. It is increasingly a topic of concern for the population and politicians, resulting in an array of preventive measures being taken, from house building regulations to speed limitations during night-time.

As children are seen to be particularly vulnerable to the adverse effects through noise (WHO, 2009), scientific research is needed to substantiate interventions to protect children efficiently.

1.2. What is noise?

Noise is unwanted sound. Physically, sound is a wave travelling through a medium, such as air, created by an emitting source and is perceived by a receiver's ear. The frequency of noise describes how high or low a sound is (the pitch), and the noise intensity describes how soft or loud it is. The sound spectrum is a combination of different frequencies and makes one sound distinguishable from another. There are two ways to describe noise. The physical description distinguishes ordered and random, wave patterns. Most musical sound creates ordered and repetitive patterns, while traffic noise, but also other noise sources such as percussion instruments, create the chaotic, random sound wave patterns.

However, the more relevant reason why some sound is perceived as *noise* is psychological in nature. Whether or not sound is perceive as noise might differ between people. Some may consider highly distorted guitar music as noise, and for others the tolling of church bells is noise. Or, as the German writer Kurt Tucholsky states: "Der eigene Hund macht keinen Lärm – er bellt nur." ("One's own dog does not make noise – it merely barks"). Time, location and personal preferences play a role in noise perception. Some studies measure the psychological aspect of noise by measuring annoyance levels specific to source. Most studies use the physical noise definition to define and quantify noise and amount of noise exposure. Most essential is the intensity of power of noise measured in decibels.

1.2.1 Decibels

The intensity of sound, the sound pressure level that we can perceive with our ear, is expressed in decibel (abbr.: dB) which it is measured on a logarithmic scale (Figure 1). A 10 dB increase in sound intensity is perceived as being about twice as loud. Whispering produces a sound of about 30 dB, while sound during a conversation amounts to about 60 dB. Being exposed to an average noise level of 85 dB or more (comparable to a sound pressure level between a toilet flushing and a running lawnmower) throughout an 8-hour workday can be dangerous and may cause long-term hearing damage. The pain threshold is reached at 130 dB, the sound equivalent of a jet engine taking off.

The European Environmental Agency defines high-intensity environmental (i.e. outdoor) noise levels as above on average 55 dB during the day and above 50 dB by night (EEA, 2020). Average noise levels over 55 dB are understood to be potentially harmful for one's health and are used as cut-offs for most descriptive and analytical statistics in noise studies.

Figure 1. The decibel scale for the human hearing range.

1.2.2. Metrics

The **L_{Aeq}** is the equivalent sound level, and describes the mean sound level for a specific duration of time, mostly 24 hours. The **L_{den}** (day–evening–night noise level) also describes noise level over 24 hours, but weights noise at evening and night higher (5 dB penalty for evening noise (18:00–23:00) and 10 dB penalty for night noise (23:00–07:00)) to adjust for the more detrimental effect of noise during these times of the day.

Not only the average noise level through the day, but also short term variation of noise over time, show their specific effect. Different kinds of noise, with a variety of characteristics – such as being startling, intermittent, uniform, showing a variety of characteristics, or being present at either night or day – will produce different reactions in exposed people. Different noise metrics were developed to measure these individual effects. Sudden noise effects are captured in the $\mathbf{N_{evt}}$ (Number of events) metric. It describes the amount of event-based sound pressure levels that exceed the background sound pressure level (in L_{Aeq}) by 3 dB measured per hour.

The Intermittency Ratio (abbr.: IR) describes the ratio of single noise events compared to the background noise (Wunderli et al., 2016). The IR takes a value from 0-100%. It indicates which proportion of the noise energy is produced by individual noise events.

1.2.3. Sources of environmental noise

Sources of environmental noise are manifold, ranging from noisy neighbours to airplanes taking off. Increasing urbanization has led to an overall increase of noise exposure and reported noise annoyance. Of note, the most relevant contributor to environmental noise by far is traffic noise, specifically the noise produced by road traffic. Transportation-related noise, i.e. noise produced by road traffic, aircraft and railways (sometimes industrial noise and wind craft noise), stand at the center of most studies assessing the effects of noise pollution on health. Road traffic noise, especially noise from highways, is often constant in nature. Aircraft noise and rail noise are both intermittent and high in volume; however, even though aircraft and rail noise share these similarities, the same level of L_{den} is perceived as more annoying in aircraft noise than in railway (Brink et al., 2019). Rail noise has a “railway bonus” (Fastl et al., 1994; Möhler, 1988). A recent study on aircraft noise around Zurich airport and its association with cardiovascular diseases found a triggering (acute) effect of aircraft noise on participants (Saucy, Schäffer, et al., 2021). In studies of children’s health and wellbeing, aircraft noise is a central and important noise exposure, especially at schools near airports, with negative impact particularly on cognitive capacities, especially reading.

1.3. Noise and health

Studies of environmental noise exposure have shown associations with a variety of health outcomes. The most recent Environmental Guidelines by the WHO (2018) identified the following key health outcomes and conducted systematic reviews for each: hearing loss and tinnitus (Śliwińska-Kowalska & Zaborowski, 2017), effects on sleep (Basner & McGuire, 2018), cardiovascular and metabolic effects (van Kempen et al., 2018), annoyance (Guski et al., 2017) and also cognitive impairment in children (Clark & Paunovic, 2018).

1.3.1 Burden of disease

The WHO estimated that at least one million healthy life years (disability-adjusted life years (abbr.: DALY)) were lost in western European countries due to environmental noise exposure (2018). These numbers include sleep disturbance (903 000 DALYs), noise annoyance (587 000 DALYs), Ischemic heart disease (61 000 DALYs), cognitive impairment in children (45 000 DALYs) and Tinnitus (22 000 DALYs) (WHO, 2011). The vast majority of DALYs can be attributed to sleep disturbance and noise annoyance. Most studies are using adult populations. Of note, only noise impact on cognitive functions has mainly been studied in children, with only few studies assessing noise impact on cognition in adults.

1.3.2 Cardiometabolic pathway

The most well-known and used pathway describing the complexity of the link between noise and health outcomes, annoyance and cognitive and emotional responses is described by Münzel et al. (2014; 2021) (Figure 2). The pathway has been adapted for several different publications and was originally based on the noise-reaction model proposed by Babisch (2002, 2014). The primary outcome of interest is the effect of noise on cardiometabolic diseases, but the depicted pathway also describes the potential effects of noise on other outcomes. There are two ways noise can induce a stress response, through a direct pathway and an indirect pathway. The indirect pathway can be activated through low level noise exposure. Noise disturbs activities, sleep and communication or/and cognitive and emotional responses, which may in turn evoke annoyance or/and depression or lead straight to a stress reaction. The direct pathway, activated through loud noise, can lead to hearing loss and/or sleep disturbances, with both also resulting in a stress response. Noise induced stress can manifest in a physiological stress reaction, affecting the autonomic nervous system and endocrine system (panel b), which in turn can lead to cardiovascular risk factors and may lead to cardiometabolic diseases.

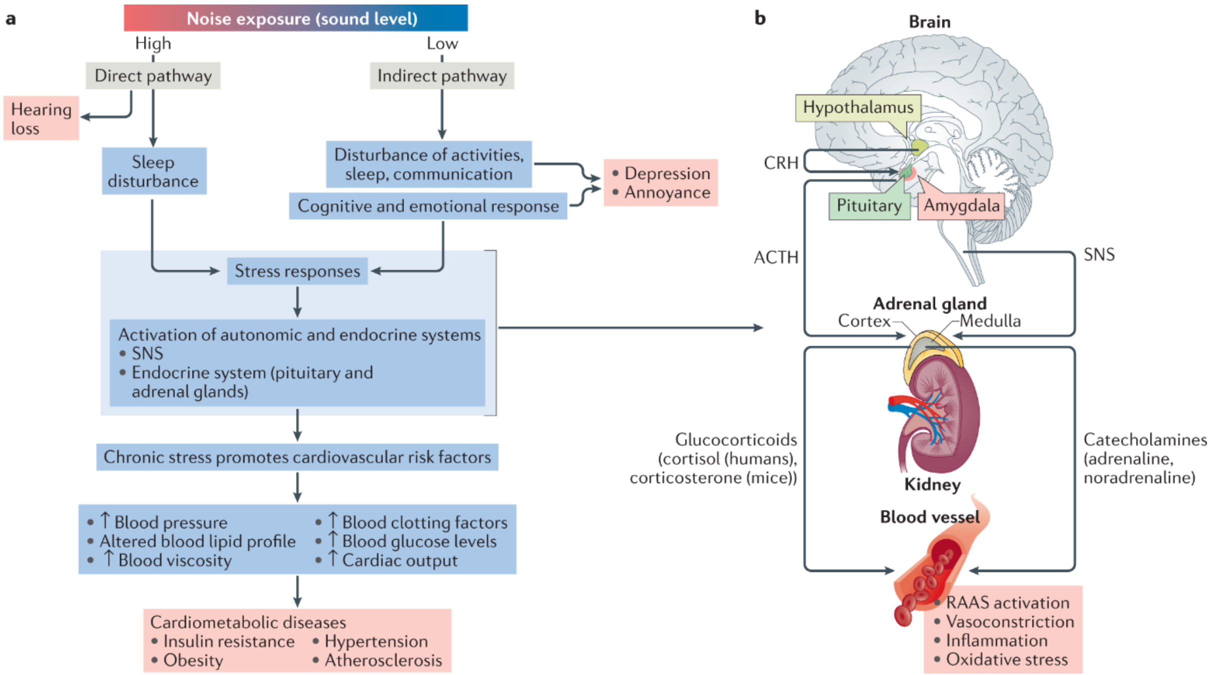

Figure 2. Noise reaction model for the direct (auditory) and indirect (non-auditory) effects of noise exposure by Münzel et al. (2021) adapted from Babisch (2002, 2014), used with permission from the author.

1.3.3 Noise health effects in children

In children the most studied outcome is cognitive function(Thompson et al., 2022), while others include behavioural and psychological effects(Schubert et al., 2019), noise annoyance (van Kempen et al., 2009), cardiometabolic effects (Bilenko et al., 2015), loss in quality sleep(Basner & McGuire, 2018) and hearing loss (Śliwińska-Kowalska & Zaborowski, 2017).

1.3.4 Behaviour and emotional disorders

About one in four people will experience mental health problems during their lifetime, with 50% occurring before the age of 14 (Kessler et al., 2005). Psychological health is essential for children to pass through the stages of development smoothly and be equipped for a healthy and happy life. In noise studies, aspects of psychological health are often measured with a behavioural screening questionnaire, the Strength and Difficulties Questionnaire (abbr.: SDQ)(Goodman, 1997). This questionnaire measures 5 domains that relate to behaviour: conduct problems, emotional problems, hyperactivity/inattention, peer problems and prosocial behaviour. The most common behavioural issue is shown to be associated with noise is hyperactivity/inattention. In a review on transportation noise and behavioural and emotional disorder Schubert and al (2019), found 15 studies on the on the effect of noise and behaviour in children and adolescent. Due to variations of study design and methods, a small meta-analysis in the review only included 3 studies on the effect of road traffic noise on behavioural outcomes (Hjortebjerg et al., 2016; Lim et al., 2018; Tiesler et al., 2013). Of all outcomes, the odds of hyperactivity/inattention indreased by 11% (OR: 1.11; 95% CI: 1.04, 1.19) and total difficulties increased by 9% (OR: 1.09; 95% CI: 1.02, 1.16) per 10 dB higher road noise. A meta-analysis of the effect of aircraft noise was conducted by Clark et al. (2021). The authors reanalysed data of three studies that had similar methodology: the Schools Environment and Health Study, the West London Schools Study, and the RANCH study with a combined number of 3998 students (Clark et al., 2013; Haines, Stansfeld, Brentnall, et al., 2001; Haines, Stansfeld, Job, et al., 2001). The data showed a significant increase of hyperactivity/inattention from aircraft noise at school by 0.17 (95% CI: 0.07, 0.28) units per 10 dB increase in aircraft noise.

1.3.5 Cognition

The EEA estimates that in 2017 on average 12400 children aged 7 to 17 were affected by aircraft noise induced reading impairment in western European countries. A review for the 2018 WHO Noise Guidelines by Clark and al. concluded that, using the GRADE criteria, the only cognitive outcome that showed moderate quality evidence (in comparison to lower quality evidence) was reading long term memory. An updated version of the review from 2022 (Thompson et al.) found moderate quality evidence for associations for aircraft noise exposure with reading and language abilities in children and moderate quality evidence against an association between the same exposure with executive functioning in children. The authors point out that other cognitive outcomes were measured, but ranged low of very low in evidence. This is mostly due to not enough longitudinal study designs or inconsistent results.

Meta-analyses on the association between noise and cognition are specifically difficult to conduct, because of considerable diversity in outcome measures and measurement tools. The following studies fall under the cognition umbrella: executive function, memory, academic performance, reading, attention and verbal and language ability, (Clark et al., 2012; Klatte et al., 2017; Papanikolaou et al., 2015; Stansfeld et al., 2010; Thompson et al., 2022; Van Kempen et al., 2010).

1.3.6 Pathways in children

Several pathways for lower cognitive functions in children through noise exposure have been proposed. One reason for the particular susceptibility to noise of children/adolescents compared to adults, might be because of disruptions during sleep. In consequence, this may might lead to low mood, fatigue and impaired task performance the next. Children and adolescents sleep longer and therefore are exposed to time windows with higher traffic intensity, be it a constant flow of road traffic or the more eventful, sleep disrupting railway or aircraft passing by (Basner et al., 2014; Clark & Paunovic, 2018). Cognition might also be influenced by noise affecting changing learning processes. Children and adolescents who are exposed to noise might feel frustration and annoyance (Evans & Lepore, 1993).

A possible outcome of this is psychological and physical stress but also learned helplessness (Evans & Stecker, 2004; Seligman, 1972). Learned helplessness may develop when people are exposed to an uncontrollable environment – the noisy environment. The characteristics of this state are a loss of motivation and a resignation leading to reduced self-esteem, decreased persistence, low self-efficacy and even depression. This in turn can results in reduced learning efficacy. Another possible pathway through which noise may directly or directly impact on cognition, is through the direct effect of noise on teachers and students in the school setting. The quality in teaching and studying might be affected through interruptions, pauses of teaching and reduced speech intelligibility during very loud noise events (Klatte et al., 2013). Students might learn to tune out noise in general, which may over time also include the teacher's voice (Evans & Lepore, 1993). Teachers and students might in general feel frustrated and stressed.

Some studies focused on how increased noise levels in classrooms are perceived by teachers and/or students. One study showed, that teachers who indicated being exposed to noise more than half the time in classrooms showed lower job satisfaction, greater lack of energy and motivation, as well as sleepiness and even interest in leaving the job. (Kristiansen et al., 2013). In the German NORAH-study of 1058 second-graders in the vicinity of the Frankfurt/Main Airport, teachers indicated severe impairments of school lessons due to noise in the form of interruptions and obvious distractions; in the same study, students reported lower well-being when at school (Bergström et al., 2015).

1.4. TraNQuiL

This doctoral thesis was part of a larger SNF project called TraNQuiL (Transportation Noise: Quantitative Methods for Investigating Acute and Long Term Health Effects). It was a collaboration between the Environmental Exposures Group at the Swiss Tropical and Public Health Institute (Swiss TPH) in Basel, Switzerland, and the Swiss Federal Laboratories for Materials Science and Technology (EMPA) in Dübendorf, Switzerland.

It consisted of three work packages, which have added to the literature on transportation noise exposure and acute and long-term health effects, especially effect in the cardiovascular system (Saucy, de Hoogh, et al., 2021; Saucy, Ragettli, et al., 2021; Saucy et al., 2020; Saucy, Schäffer, et al., 2021; Saucy et al., 2019; Vienneau et al., 2019; Vienneau et al., 2022).

2. Methods

2.1. Aims and objectives

The primary aim of this dissertation is to contribute to a better understanding on how chronic exposure to environmental noise influences adolescent health.

This aim is operationalized with following objectives which allow to address different facets.

> Objective 1. Analyse the association between transportation noise and adolescent cognitive functions and behaviour.
> Objective 2. Describe and quantify the role of transportation noise at home, at school and their relationship.
> Objective 3. Evaluate the role of different noise characteristics in impacting health outcomes
> Objective 4. Use parameters that modify transportation noise reaching the participants, such as bedroom orientation towards the loudest side of the house, and determine their role in noise exposure.

2.2 Article on noise and children's health

The article: "Wie wirkt Lärm auf Kinder" ("How does noise affect children") provides an introduction to this thesis. It was written for Swiss pediatricians and published in "Paediatrica", the journal of the Swiss National Pediatric Society. Its purpose was to update and translate knowledge for the main stakeholders involved in providing health care for Swiss children. The article presents a comprehensive narrative review of the current status of knowledge on the subject and concludes with recommendations and suggested activities to inform pediatricians and facilitate interaction with and care for their patients, and enable them to help to mitigate and reduce risks and potential detrimental outcomes associated with chronic noise exposure for children in their care. The original article was available in German and French and has been translated to English for this thesis.

2.3. Study description

All objectives were addressed with two studies based on methods described below:

2.3.1 Population

The participants were originally recruited for the study *Health effects related to mobile phone use in adolescents* (abbr.: HERMES). Participants were recruited in central Switzerland and the Basel area (Figure 3). The data was collected in two waves, between June 2012 and February 2014 (N_{wave1}: 442) and between June 2014 and February 2016 (N_{wave2}: 457). The two cohorts were treated as one large cohort of 899 adolescents aged 10-17.

Data collection was conducted for each participant at two points in time, with one year in between. The outcomes of interest were collected with help of a questionnaire (behavioural data) and cognitive testing (memory and concentration). Additional personal information, including socio-demographic information and information on sleeping away or towards the loudest street passing by the house were also collected.

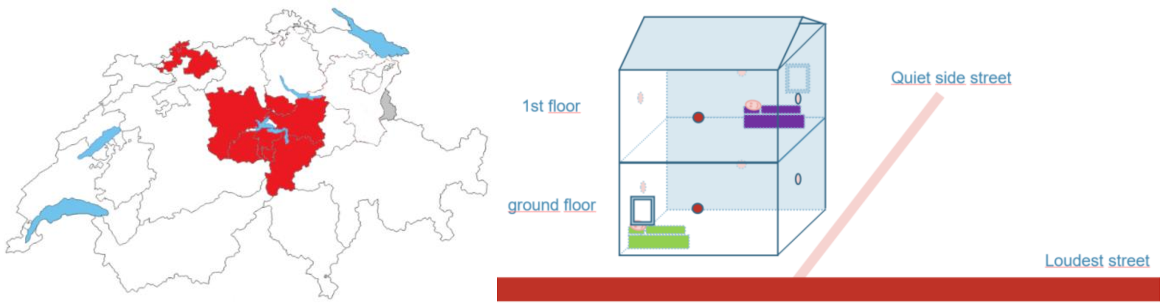

Figure 3. Cantons of participants and description of bedroom orientation variable (green: window orientation facing the loudest street, purple: window orientation facing away from the loudest street)

2.2.2 Exposure

Noise exposure per participant was extracted from noise pollution maps (road, rail, aircraft and total noise (i.e. all noise sources combined)) – where possible, the data was matched to the floor of residence in the house (Karipidis et al., 2014; Vienneau et al., 2019). Exposure to aircraft noise and rail traffic noise was negligible and therefore road traffic noise was the primary and central noise exposure in the analyses. Noise metrics were L_{den}, L_{night}, L_{day}, N_{evt} and IR at home and at school location. Information about local greenness and air pollution was also available and controlled for.

2.2.3 Statistical Analysis

Two main analyses were conducted to determine the cross-sectional and the longitudinal relationship between noise and all outcomes (Objective 1). The cross-sectional analyses were multilevel, multivariable linear analyses with the individual as the cluster variable, controlling for the fact that measurements of the same individual are correlated. This analysis was used to give insight into the long-term effects of noise exposure, even though the causal interpretations need to take into consideration the limitations of the design. More causal interpretation was possible through the longitudinal analyses, which measured the difference within the outcome of one participant with their noise exposure with a multivariable linear regression analysis. This allowed us to measure whether changes in behaviour or cognition throughout one year where associated with the noise level.

Additional analyses were done using a variety of noise metrics (Objective 3) and differentiating between the two locations – home and school (Objective 2). The variable bedroom orientation was used as covariate, and in interaction analyses (Objective 4).

Missing data was addressed with the multiple imputation method (Sterne et al., 2009b).

2.3 Ethical Consideration

This study was funded by the Swiss National Science Foundation (abbr.: SNSF) grant number: grant no. 324730_173330. The original HERMES-study received ethical approval from the ethical committee of Lucerne, Switzerland on May 9, 2012 (Ref. Nr. EK 12025). The ethical approval for secondary use of the HERMES-data was received by the committees Northwest – and Central Switzerland on 08.06.2018 (Project-ID, 2018–00980).

3 How does noise affect children?

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3.1 German Version

Wie wirkt Lärm auf Kinder?

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Einleitung

Lärm und seine Auswirkungen sind schon lange ein Thema. So wird berichtet, dass zu Zeiten des alten Roms der Wagenverkehr im Zentrum der Stadt eingeschränkt wurde, mit der Absicht die Lärmbelästigung zu reduzieren. Mit dem Beginn der Industrialisierung in der zweiten Hälfte des 18. Jahrhunderts trugen Motoren und Maschinen zunehmend zur Lärmbelastung in den Städten bei. Das weckte schon damals Widerstand. Julia Barnett Rice, die Ehefrau eines wohlhabenden Geschäftsmanns in New York City, protestierte 1906 gegen den Lärm der lauten Signalhörner der Schlepper in der Hudson Bay und schrieb einen Artikel mit dem Titel: *«In an Effort to Suppress Noise»*[1]. Sie interviewte verschiedene Betroffene zu dem Thema und argumentierte schon zu der Zeit mit der Fachmeinung eines Dr. John H. Girdner eines Krankenhauses in Nähe zum Wasser, dass Kinder besonders lärmempfindlich sind:

«City noises exert a deleterious effect on the human system; this is especially marked in the case for invalids and children. Noise is a most potent factor in producing functional diseases of the brain and nervous system, not alone by its direct action, but by destroying sound, refreshing sleep.»[1]

In Deutschland war es Theodor Lessing, der 1908 ein Buch mit dem Titel: «Ein Recht auf Stille» herausgab und den ersten «Antilärm-Verein» gründete.

Aber was ist eigentlich Lärm? Jeder ist täglich Geräuschen ausgesetzt. Aber wann wird ein Geräusch zu Lärm? Eine streng wissenschaftliche Definition für Lärm gibt es nicht. Generell wird Lärm als unerwünschter Schall beschrieben. Am häufigsten – und auch am häufigsten wissenschaftlich untersucht – ist der Verkehrslärm, zum Beispiel von der Strasse, dem Bahn- oder dem Luftverkehr. Weitere häufig genannte störende Lärmquellen sind Bau- und Industrielärm, Nachbarschaftslärm (laute Musik, Haushaltsgeräte etc.), Glockengeläut oder Freizeitlärm.

Lärm wird als Schalldruckpegel auf der Dezibel-Skala (dB) gemessen. In der Lärmwirkungsforschung ist neben dem Mittelwert der Geräuschbelastung (L_{Aeq}) auch der zeitlich gewichtete Mittelwert $L_{DEN(Day\text{-}Evening\text{-}Night)}$ gebräuchlich. Dabei wird bei der 24-Stunden-Mittelwertbildung für die Abend- und Nachtstunden 5 bzw. 10 dB addiert und damit dem Umstand Rechnung getragen, dass Lärm in der Nacht als störender als am Tag empfunden wird.

Wie wirkt chronischer Lärm auf die Gesundheit?

Das Wort «Lärm» leitet sich aus dem Italienischen «all'arme» (zu den Waffen) ab und zeigt anschaulich die Auswirkungen auf den Menschen. Lärm erzeugt eine Stressreaktion. Dabei wird sowohl das sympathische Nervensystem, wie auch die Hypothalamus-Hypophysen-Nebennierenrinden-Achse – auch Stressachse genannt – aktiviert[2]. In einer der wenigen Studien zu den hormonellen Reaktionen auf Lärm bei Kindern wurde bei 217 Kindern im mittleren Alter von zehn Jahren nach der Eröffnung eines neuen Flughafens in München eine signifikante Erhöhung von Adrenalin, sowie Noradrenalin festgestellt[3].

Eine chronische Stressreaktion durch Lärm kann langfristig vielfältige negative Auswirkungen auf die Gesundheit haben. Dabei spielen die Art des Lärms, die Situation und die Prädisposition eine wichtige Rolle. Die bekanntesten gesundheitlichen Probleme, die mit Lärm in Verbindung gebracht werden, sind die subjektive Belästigung, schlechter Schlaf, kardiovaskuläre Erkrankungen sowie Einflüsse auf den Metabolismus und die mentale Gesundheit bei Erwachsenen[4]. Weniger Aufmerksamkeit geweckt haben dagegen die negativen Auswirkungen von Lärm auf die Gesundheit von Kindern. Es wird argumentiert, dass Kinder besonders lärmempfindlich sind, da sie noch in ihrer Entwicklungs- und Wachstumsphase sind. Durch das frühere Zubettgehen und die längere Schlafzeit sind Kinder stärker im Schlaf mit Lärm konfrontiert und daher störanfälliger[5].

Kognitive Auswirkungen

Die am meisten untersuchten gesundheitlichen Auswirkungen auf Kinder durch chronischen Lärm sind Beeinträchtigungen der kognitiven Fähigkeiten, wie Lesefähigkeit, Gedächtnisleistung oder Aufmerksamkeit – häufig erforscht in Schulen, die nahe Flughäfen liegen und Fluglärm ausgesetzt sind.

Eine erste longitudinale Studie wurde 2001 in England bei 275 Kindern im Alter von acht bis elf Jahren durchgeführt[6]. Hier wurden Kinder in der Nähe eines Londoner Flughafens mit einer Kontrollgruppe ohne Fluglärm in ihrem Leseverständnis und ihrem Aufmerksamkeitsvermögen verglichen und nach einem Zeitraum von einem Jahr ein weiteres Mal untersucht. In Querschnittsanalysen waren unter Berücksichtigung des Alters, dem sozioökonomischen Status und der Muttersprache die Lesefähigkeit und die Konzentrationsfähigkeit bei den lärmexponierten Kindern signifikant schlechter als bei den nicht-exponierten Kindern. In longitudinalen Analysen wurden für die Entwicklung der Lesefähigkeit und Konzentrationsfähigkeit innerhalb eines Jahres tendenziell die gleichen Assoziationen gefunden. Diese waren jedoch statistisch nicht signifikant. Die Studie prüfte auch die Hypothese, ob sich die Kinder innerhalb eines Jahres an den Lärm gewöhnten und konnte dafür keine Evidenz finden.

Eine weitere prospektive Kohortenstudie mit 326 Kindern in München machte sich zunutze, dass ein alter Flughafen stillgelegt wurde, während zur gleichen Zeit ein neuer Flughafen in Betrieb genommen wurde[7]. Vier Gruppen von Kindern, die im Durchschnitt gleich alt waren (zehn Jahre) und den gleichen sozioökonomischen Status hatten, wurden untersucht. Zwei dieser Gruppen wohnten in der Umgebung des alten Flughafens, zwei in der Umgebung des neuen Flughafens. Dabei war jeweils eine Gruppe lärmexponiert und die andere nicht. Die Kinder wurden einmal vor dem Wechsel der Aktivität der Flughäfen und zweimal danach untersucht. Lärmexponierte Kinder in der Nähe des alten Flughafens zeigten in der ersten Untersuchung, als der Flughafen noch in Betrieb war, ein reduziertes Langzeitgedächtnis und Leseverständnis im Vergleich zu ihrer nicht exponierten Kontrollgruppe. Zwei Jahre nach dem Schliessen des Flughafens war dieser Unterschied ver-

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schwunden. Auf der anderen Seite wurde um den neuen Flughafen bei den lärmexponierten Kindern reduzierte Gedächtnisleistung und Leseverständnis im Vergleich zu ihrer nicht exponierten Kontrollgruppe beobachtet.

Diese Ergebnisse stehen im Einklang mit der grossen internationalen Querschnittstudie RANCH, bei der 2844 neun- bis zehnjährige Kinder aus 89 verschiedenen Schulen um Flughäfen in Spanien, Holland und Grossbritannien untersucht wurden[8]. Unter Berücksichtigung von Störgrössen wie sozioökonomischem Status und mütterlicher Bildung nahmen mit zunehmendem Flug- und Strassenlärm auf dem Schulgelände die Lesefähigkeit und die Gedächtnisleistung der Schulkinder ab. Eine separate Analyse der holländischen Daten fand mit zunehmender Strassenlärmexposition beim Schulhaus eine Zunahme der Fehlerrate in einem kognitiven Test. Eine neue ähnliche Querschnittstudie um den Flughafen Frankfurt bei 1243 Schülern im Alter von sieben bis zehn Jahren kam zum Schluss, dass eine 20 dB höhere Lärmbelastung mit einer um zwei Monate verzögerten Leseleistung der Kinder assoziiert ist[9].

Zusammenfassend lässt sich festhalten, dass die bisherigen Studien bei Kindern zur Kognition hauptsächlich negative Zusammenhänge des Lärms am Schulort mit der Informations- und Sprachverarbeitung, sowie dem Problemlösen und der Gedächtnisleistung nachgewiesen haben. Es gibt verschiedene Hypothesen wie diese Wirkungen zustande kommen. So wird beispielsweise postuliert, dass die Stresswirkung oder die Erfahrung, dem Verkehrslärm machtlos ausgeliefert zu sein, bei Kindern zu Resignation, Demotivation und anderen Verhaltensproblemen führt, die sich schlussendlich auf die Lernleistung auswirken. Umgekehrt könnten lärmbedingte Motivationseinbussen beim Lehrer zu einer verminderten Lehrleistung des Lehrers führen. Ganz trivial könnte der Verkehrslärm aber auch die Verständlichkeit des Lehrers im Schulzimmer beeinflussen oder die Überflüge von Flugzeugen könnten zu wiederholten kurzen Unterbrechungen und so zu ineffizientem Unterricht führen.

Verhaltensprobleme und Depressionen

Die empirische Datenlage zu lärmbedingten Verhaltensauffälligkeiten und Depressionen bei Kindern ist nicht gross und teilweise widersprüchlich[4]. In einer grossen dänischen Kohortenstudie mit 46 940 siebenjährigen Kindern zeigte sich, dass pro 10 dB Erhöhung der kumulativen Lärmexposition am Wohnort die Hyperaktivität, gemessen mit dem *«Strengths and Difficulties Questionnaire (SDQ)»*, signifikant um 9% zunahm[10]. In einer anderen Querschnittsstudie mit 2897 sieben- bis elfjährigen Kindern aus Barcelona war die Verkehrslärmexposition des Schulzimmers mit einem erhöhten Risiko für Aufmerksamkeitsdefizitsymptome, jedoch nicht mit einem erhöhten SDQ-Score assoziiert. Die einzige longitudinale Studie zu Verhaltensproblemen bei Kindern verwendete die von den Eltern berichtete Verkehrslärmbelästigung als Surrogat für die tatsächliche Lärmexposition am Wohnort. Bei den 1185 Kindern aus Bayern war das Neuauftreten von Verhaltensproblemen zwischen dem 5./6. und dem 9./10. Lebensjahr signifikant mit der Strassenverkehrslärmbelästigung der Eltern assoziiert. Interessanterweise waren aber nicht wie bei der spanischen Studie die Hyperaktivität betroffen, sondern vor allem die SDQ-Subskalen «emotionale Probleme» und «Aggressionen». In der oben erwähnten Studie um den Londoner Flughafen unterschieden sich lärmexponierte und nicht exponierte Kinder hinsichtlich Ängstlichkeit und Neigung zu Depressionen nicht[6].

Lärmbelästigung bei Kindern

Es gibt eine Vielzahl von Studien zur subjektiven Lärmbelästigung bei Erwachsenen, die zeigen, dass sich rund 15% der Erwachsenen in Europa bzw. der Schweiz durch Lärm belästigt fühlen. Die oben erwähnte RANCH-Studie ist eine der wenigen Belästigungserhebungen bei Kindern. Sie fand, dass der Anteil von Kindern, die sich vom Fluglärm belästigt fühlten von 5.1% bei 50 dB ($L_{Aeq7\text{-}23}$) auf 12.1% bei 60 dB anstieg[11]. Auch in der Londoner Flughafenstudie waren der Grad der Belästigung und der selbstberichtete Stresslevel bei fluglärmexponierten Kindern höher als bei Nichtexponierten. Diese Studien deuten darauf hin, dass sich Kinder zwar auch durch Lärm belästigt fühlen, dies aber weniger häufig angeben als Erwachsene. Ein Grund für den geringeren Anteil von lärmbelästigten Kindern im Vergleich zu Erwachsenen könnte sein, dass Kinder die stressende Wirkung von Lärm zwar empfinden, jedoch diesen Stress nicht analysieren und dem Lärm zuordnen können.

Kardiometabolische Effekte

Die Auswirkungen von Verkehrslärm auf kardiovaskuläre Krankheiten bei Erwachsenen haben sich in vielen Studien bestätigt[2]. Eine Metaanalyse kam auf der Basis von sieben longitudinalen Studien zum Schluss, dass pro 10 dB Zunahme des Strassenverkehrslärms (L_{DEN}) das Risiko für ischämische Herzkrankheiten signifikant um 8% ansteigt[12]. Bei Kindern wurden hauptsächlich der Blutdruck und Veränderungen im Puls untersucht. In der PIAMA-Kohortenstudie wurde der Blutdruck von 1432 zwölf Jahre alten Kindern mit deren Exposition zu Strassenlärm verglichen und kein statistisch signifikanter Zusammenhang beobachtet[13]. In der RANCH-Studie war die Fluglärmexposition zuhause signifikant und am Schulort nicht-signifikant mit erhöhtem Blutdruck assoziiert. Jedoch wurde für zunehmenden Strassenlärm am Schulort eine Abnahme des Blutdrucks beobachtet, was in der Studie nicht erklärt werden konnte. Eine neue Meta-Analyse von 13 Studien bei Kindern fand keinen signifikanten Zusammenhang zwischen Blutdruck und Lärmexposition[14]. Jedoch waren viele Studien methodisch limitiert. Die widersprüchliche Datenlage der wenigen Studien könnte auf die kürzere kumulative Expositionszeit bei Kindern zurückzuführen sein, da damit kleinere potentielle Effekte im Vergleich zu Erwachsenen zu erwarten wären. Auch wenn bei Kindern nur schwache Einflüsse des Lärms auf das Herz-Kreislaufsystem auftreten würden, könnte sich dies langfristig dennoch negativ auf die kardiovaskuläre Gesundheit im Erwachsenenalter auswirken.

Bei Erwachsenen wurde in mehreren Kohortenstudien beobachtet, dass Verkehrslärm mit einem erhöhten Risiko für Übergewicht oder Diabetes assoziiert ist[4]. In der oben erwähnten dänischen Kohortenstudie bei mehr als 40 000 Kindern nahm das Risiko für Übergewicht im Alter von sieben Jahren um 6% zu, pro 10 dB Zunahme der Strassenlärmbelastung am Wohnort während der Schwangerschaft oder während den ersten sieben Lebensjahren. Diese Ergebnisse wurden kürzlich in einer norwegischen Studie nur teilweise bestätigt[15]. In der Studienpopulation von 22 975 Kindern wurde zwischen der Strassenlärmexposition der Mutter während der Schwangerschaft und dem BMI des Kindes bei Geburt eine negative Assoziation festgestellt, und mit dem BMI im Alter von acht Jahren wie in der dänischen Studie eine positive Assoziation. In der norwegischen Studie hatte die Strassenlärmexposition in der Kindheit jedoch keinen Einfluss auf den BMI.

Schlaf

Neben der Stresswirkung können auch lärmbedingte Schlafprobleme langfristig die Gesundheit beeinträchtigen, da Schlaf eine wichtige Funktion für die Gesundheit und die Entwicklung von Kindern hat und Kinder eine längere Schlafzeit benötigen. In einer neuen Übersichtsarbeit sind fünf Studien zum Einfluss von Verkehrslärm auf Schlafprobleme bei Kindern beschrieben[5)]. In all diesen Studien mit Kindern im Alter zwischen sieben und dreizehn Jahren wurden schwache negative Zusammenhänge zwischen Verkehrslärmexposition und selbstberichteter Schlafqualität beobachtet. Die Erhebungen sind jedoch nicht einheitlich in Bezug auf die festgestellten Schlaf- und Expositionsmasse, so dass sich nicht ableiten lässt, ab welcher Lärmbelastung negative Effekte auf den Schlaf zu erwarten sind. Nur eine von diesen fünf Studien erhob zusätzlich mittels Aktigraphie bei 80 Kindern auch objektive Daten zur Schlafqualität[16)]. Dabei wurde aber kein Zusammenhang zwischen modellierter Strassenlärmexposition und objektiv gemessener Schlaflatenz sowie Bewegungen und Wachphasen im Schlaf beobachtet. In der Studie wurde jedoch in Frage gestellt, ob die Aktigraphie eine gute Messmethode der Schlafqualität für Kinder darstelle. Drei kleine Studien mit insgesamt 47 Teilnehmenden untersuchten Effekte von Lärm im Spital bei Kleinkindern. Alle drei Studien fanden Hinweise, dass sich Lärm auch bei unter fünfjährigen Kindern auf die Schlafqualität auswirkt.

In einer Sekundärdatenanalyse wurde versucht zu klären, ob die in der RANCH und der Münchner Flughafenstudie beobachteten kognitiven Effekte des Fluglärms auf lärmbedingte Schlafprobleme zurückzuführen waren. Dies konnte aber mit den Daten nicht bestätigt werden.

Auswirkungen auf das Gehör

Neben den bisher beschriebenen Lärmeffekten, die schon bei moderater Umweltlärmexposition beobachtet werden, sind hohe Lärmexpositionen für das kindliche Gehör ein Risikofaktor. Dabei sind Audio-Player eine wichtige Lärmquelle, die potentiell Auswirkungen auf das Gehör haben können. Um Schäden hervorzurufen reicht entweder ein kurzes sehr lautes Geräusch (> 120dB) aus, oder aber auch eine länger andauernde Einwirkung von 85 dB oder mehr. Im Gegensatz zu akuten Hörschäden, werden die langsam entstehenden Hörschäden bei einer chronischen Lärmwirkung anfangs kaum wahrgenommen, was zu einer Unterschätzung der entsprechenden Gesundheitsgefahren führt. Dennoch schienen in einer Umfrage Jugendliche der langfristigen Gefahr durch zu laute Musik bewusst zu sein[17)]. Das äusserte sich aber nicht unbedingt in einem entsprechenden Handeln. In einer Interventionsstudie, in der Jugendliche, die ihre Musik laut hörten, über die negativen Auswirkungen des lauten Musikhören aufgeklärt wurden, gaben nur die Hälfte an, ihre Musik zukünftig leiser hören zu wollen[17)]. Dies ist kein überraschender Befund, unterstreicht jedoch, dass es nötig sein wird, dieses verhaltensbasierte Gesundheitsrisiko durch den «erwünschten» Lärm bei Jugendlichen in Zukunft effizienter anzugehen. Es ist auch zu beachten, dass Audio-Player oft genutzt werden um Umweltlärm auszugrenzen. Insofern gibt es eine Interaktion dieser Exposition mit störendem Umweltlärm.

Was kann man in der Praxis gegen Lärm machen?

Der Effekt von Lärm auf die Gesundheit von Kindern ist ein Problem, das in der ärztlichen Praxis schwer zu fassen und quantifizieren ist. Wie erläutert, ist Lärm häufig nur ein Faktor unter mehreren, der zu Verstärkung von unerwünschten Symptomen führt, sich aber im Kindesalter nur selten in einer manifesten Erkrankung äussert.

Es stellt sich somit die Frage, was ein behandelnder Arzt in diesem Zusammenhang tun kann. Zum einen ist es hilfreich, wenn Ärzte ein Bewusstsein für das Problem entwickeln und das Wissen auch im Dialog ihren Patienten weitergeben, dass Lärmbelästigung auch im Kindesalter nicht nur «nervenaufreibend» ist, sondern kurz- und längerfristig körperliche und seelische Auswirkungen auf Kinder hat. Bei Konsultationen wegen Hyperaktivität, Verhaltensproblemen, Schlafstörungen, Müdigkeit und Schulschwierigkeiten sollte Lärm in jedem Fall ein Thema im ärztlichen Gespräch sein. Eltern sollten entsprechend sensibilisiert werden, auch um Optionen zu erwägen, wie die Lärmexposition der Familie, und insbesondere der Kinder präventiv minimiert werden kann.

Konkrete Möglichkeiten, Lärm im Alltag eines Kindes anzusprechen:

- Wie sieht die Situation für Aussenlärm z. B. von Flugzeugen oder Zügen aus? Gibt es Möglichkeiten sich davor zu schützen? Ist das Kinderzimmer auf eine leise Strasse ausgerichtet?
- Welche potentiellen Lärmquellen gibt es in der Nacht? Wenn sich die Eltern im Nebenraum aufhalten, wie laut hört man ihre Geräusche im Nebenzimmer?
- Sind die Nachbarn laut und länger abends gesellig? Könnte man diesen Lärm durch Kommunikation mit den Nachbarn und Wissen um deren Zimmeraufteilung einschränken?
- Gibt es Lärmquellen im Haushalt die reduziert werden können? Gibt es dauernd nebenher laufende Fernseher oder Musik?
- Gibt es in Haushalten mit vielen Kindern Orte – Ruheinseln – zu denen sich diese zurückziehen können?
- Kinderspielzeuge können beim Kauf auf Lärm hin getestet werden. Regeln für lautes Spielzeug können gemeinsam festgelegt werden und Momente der Ruhe eingeführt werden, gerade beim Zubettgehen.
- Kennen die Kinder das Risiko von Hören lauter Musik über Audio-Player? Ist ihnen bewusst, dass die Musik nicht zu laut abgespielt werden sollte? Gibt es Regeln, damit die Player nicht permanent genutzt werden und es Platz für Ruheinseln gibt?

Als Arzt lässt sich das Thema Lärm auch in der Klinik oder dem Praxisalltag angehen. Es ist allgemein bekannt, dass die Schlafqualität von Patienten in Krankenhäusern reduziert ist. Ein wichtiger beitragender Faktor dieser reduzierten Schlafqualität ist der Lärm durch Geräte, Mitarbeiter und andere Patienten. Lärmmessungen in Krankenhauszimmern ergaben, dass die Lärmexposition im Mittel höher war als 50 dB – in Einzelfällen sogar über 60 dB[5)]. Die WHO empfiehlt in Kliniken einen Lärmpegel von 40 dB in den Gängen und 30 dB in den Patientenzimmern. Weiter empfehlen sich festgelegte Ruhezeiten, während denen Mitarbeitende, Besucher und Patienten angehalten werden, leise zu sein. Um Mitarbeiter, Besucher und Patienten für das Problem von übermässigem Lärm zu sensibilisieren, können speziell dafür entwickelte Leuchtanzeigen installiert werden, die ein Überschreiten der vorgesehenen Lärmgrenzwerte anzeigen.

Referenzen:

1) Rice JB. In an Effort to Suppress Noise. The Forum 1906;37.
2) Münzel T, Sørensen M, Gori T, Schmidt FP, Rao X, Brook J, et al. Environmental stressors and cardiometabolic disease: part I–epidemiologic evidence

supporting a role for noise and air pollution and effects of mitigation strategies. European heart journal. 2017;38(8):550-6.
3) Evans GW, Bullinger M, Hygge S. Chronic noise exposure and physiological response: A prospective study of children living under environmental stress. Psychological science. 1998;9(1):75-7.
4) Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S, et al. Auditory and non-auditory effects of noise on health. Lancet. 2014;383(9925):1325-32.
5) Basner M, McGuire S. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep. International journal of environmental research and public health. 2018;15(3):519.
6) Haines MM, Stansfeld SA, Job RS, Berglund B, Head J. A follow-up study of effects of chronic aircraft noise exposure on child stress responses and cognition. International Journal of Epidemiology. 2001;30:839-45.
7) Hygge S, Evans GW, Bullinger M. A prospective study of some effects of aircraft noise on cognitive performance in schoolchildren. Psychological science. 2002;13(5):469-74.
8) Stansfeld SA, Berglund B, Clark C, Lopez-Barrio I, Fischer P, Öhrström E, et al. Aircraft and road traffic noise and children's cognition and health: a cross-national study. The Lancet. 2005;365(9475):1942-9.
9) Klatte M, Spilski J, Mayerl J, Möhler U, Lachmann T, Bergström K. Effects of aircraft noise on reading and quality of life in primary school children in Germany: Results from the NORAH study. Environment and Behavior. 2017;49(4):390-424.
10) Hjortebjerg D, Andersen AMN, Christensen JS, Ketzel M, Raaschou-Nielsen O, Sunyer J, et al. Exposure to road traffic noise and behavioral problems in 7-year-old children: A cohort study. Environmental health perspectives. 2016;124(2):228.
11) Van Kempen EE, Van Kamp I, Stellato RK, Lopez-Barrio I, Haines MM, Nilsson ME, et al. Children's annoyance reactions to aircraft and road traffic noise. The Journal of the Acoustical Society of America. 2009;125(2):895-904.
12) Van Kempen EE, Casas M, Pershagen G, Foraster M. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cardiovascular and Metabolic Effects: A Summary. International journal of environmental research and public health. 2018;15(2):379.
13) Bilenko N, Rossem Lv, Brunekreef B, Beelen R, Eeftens M, Hoek G, et al. Traffic-related air pollution and noise and children's blood pressure: results from the PIAMA birth cohort study. European journal of preventive cardiology. 2015;22(1):4-12.
14) Dzhambov, AM., Dimitrova, DD. Children's blood pressure and its association with road traffic noise exposure–A systematic review with meta-analysis. Environmental research, 2017; 152:244-255.
15) Weyde KV, Krog NH, Oftedal B, Magnus P, White R, Stansfeld S, et al. A longitudinal study of road traffic noise and body mass index trajectories from birth to 8 years. Epidemiology. 2018.
16) Öhrström E, Hadzibajramovic E, Holmes M, Svensson H. Effects of road traffic noise on sleep: Studies on children and adults. Journal of environmental psychology. 2006;26(2):116-26.
17) Martin WH, Martin W, Griest SE, Lambert W. How loud is your music? Beliefs and practices regarding use of personal stereo systems. 33rd Annual Hearing Conservation Conference of the National Hearing Conservation Association Portland, Oregon; 2008.

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3.2 French Version

Bruit – quel effet sur les enfants?

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Traduction: Rudolf Schlaepfer, La Chaux-de-Fonds

Introduction

Le bruit et ses répercussions sont depuis longtemps un sujet de discussion. On relate en effet que dans la Rome antique le trafic des chars a été limité au centre ville afin de réduire les nuisances sonores. Dès la deuxième moitié du 18ème siècle, avec l'industrialisation les moteurs et les machines contribuent de plus en plus à la pollution sonore. Cela a occasionné des résistances déjà à l'époque. Julia Barnett Rice, épouse d'un riche commerçant de New York City, protesta en 1906 contre le bruit de corne des cargos dans la baie de Hudson, en écrivant un article intitulé *«In an Effort to Suppress Noise»*[1]. Elle interviewa des personnes concernées et argumenta déjà, en se basant sur l'avis professionnel du Dr John H. Girdner d'un hôpital situé en proximité de la rivière, que les enfants étaient particulièrement sensibles au bruit:

«City noises exert a deleterious effect on the human system; this is especially marked in the case for invalids and children. Noise is a most potent factor in producing functional diseases of the brain and nervous system, not alone by its direct action, but by destroying sound, refreshing sleep.»[1]

En Allemagne, c'est Theodor Lessing qui édita en 1908 un livre intitulé «Ein Recht auf Stille» et qui fonda le première association antibruit.

Mais qu'est-ce que le bruit? Tout le monde est quotidiennement exposé à des bruits. Mais à partir de quand le bruit supportable devient-il nuisance? Il n'existe pas de définition strictement scientifique du bruit. Généralement, le bruit est défini comme étant un son indésirable. Il s'agit le plus souvent du bruit du trafic routier, ferroviaire ou aérien, les bruits par ailleurs le plus souvent investigués scientifiquement. D'autres sources de bruits dérangeants fréquemment mentionnées sont les chantiers, les industries, le voisinage (musique très forte, appareils ménagers etc.), les cloches et des bruits occasionnés par des loisirs.

Le bruit est mesuré en tant que niveau de pression acoustique, exprimé en décibels (dB). La recherche sur les effets du bruit utilise outre le niveau sonore moyen (L_{Aeq}) aussi l'indicateur du niveau de bruit global pendant une journée (jour, soir et nuit) L_{DEN} ($L_{Day\text{-}Evening\text{-}Night}$). On ajoute à la moyenne de 24 heures pour les heures du soir 5 dB et nocturnes 10 dB, pour tenir compte du fait que nous sommes plus sensibles au bruit au cours de ces périodes.

Quel effet a la bruit chronique sur la santé?

Le mot allemand «Lärm» vient de l'italien «all'arme» (aux armes) et illustre bien l'effet sur l'homme. Le bruit provoque une réaction de stress. Cela active autant le système nerveux sympathique que l'axe hypothalamus-hypophyse-surrénales – nommé aussi l'axe du stress[2]. Une des rares études sur les réactions hormonales au bruit chez l'enfant, effectuée après l'ouverture d'un nouvel aéroport à Munich auprès de 217 enfants âgés en moyenne de 10 ans, a mis en évidence une augmentation significative du taux d'adrénaline et de noradrenaline[3].

Une réaction de stress chronique au bruit peut avoir à long terme des effets néfastes sur la santé. La nature du bruit, la situation et la prédisposition jouent une rôle important. Les problèmes de santé le plus souvent associés au bruit sont la gêne personnelle, un mauvais sommeil, les maladies cardiovasculaires ainsi que des effets sur le métabolisme et la santé mentale à l'âge adulte[4]. Les effets dommageables du bruit sur la santé des enfants n'ont par contre pas suscité le même intérêt. On argumente que les enfants sont particulièrement sensibles au bruit parce qu'ils se trouvent dans la phase de croissance et de développement. Du fait qu'ils se couchent plus tôt et ont un sommeil plus long, les enfants sont davantage confrontés au bruit pendant le sommeil et aux troubles qu'il engendre[5].

Effets cognitifs

Les troubles des facultés cognitives, comme la lecture, la mémoire ou l'attention, sont les effets sur la santé des enfants occasionnés par le bruit les plus fréquemment étudiés – souvent dans des écoles situées à proximité d'aéroports et exposées au bruit aérien.

La première étude longitudinale a été faite en 2001 en Grande Bretagne auprès de 275 enfants âgés de 8 à 11 ans[6]. La compréhension de la lecture et la faculté d'attention d'enfants vivant à proximité d'un aéroport de Londres ont été comparées à celles d'un groupe d'enfants non exposés au bruit aérien et contrôlées après une année. En tenant compte de l'âge, de la situation socioéconomique et de la langue maternelle, les analyses transversales ont révélé une aptitude à la lecture et une capacité de concentration significativement moins bonnes des enfants exposés au bruit par rapport aux enfants non exposés. L'analyse longitudinale après une année a montré les mêmes tendances – bien que statistiquement non significatives – pour le développement de l'aptitude à la lecture et de la capacité de concentration. L'étude a aussi vérifié l'hypothèse selon laquelle les enfants s'habituent au bruit au courant d'une année, sans constater d'évidence.

Une autre étude prospective d'une cohorte de 326 enfants a profité du fait qu'à Munich en même temps un ancien aéroport a été désaffecté et un nouveau mis en service[7]. Ont été suivis quatre groupes d'enfants ayant le même âge moyen (10 ans) et le même niveau socio-économique. Deux groupes, dont l'un exposé au bruit et l'autre pas, vivaient à proximité de l'ancien respectivement du nouvel aéroport. Les enfants furent examinés une fois avant et deux fois après le changement d'activité des deux aéroports. Les enfants exposés au bruit à proximité de l'ancien aéroport montraient lors du premier examen, alors que l'aéroport était encore en fonction, une mémoire à long terme et une compréhension de la lecture réduites comparé au groupe non exposé. Deux années après la fermeture de l'aéroport cette différence avait disparu. D'autre part une mémoire et une compréhension de la lecture réduites ont été constatées chez les enfants vivant à proximité de l'aéroport nouvellement construit en comparaison avec le groupe contrôle non exposé au bruit aérien.

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Ces résultats correspondent à ceux de la grande étude transversale internationale RANCH qui a examiné 2'844 enfants de 9 à 10 ans de 89 écoles différentes proches d'aéroports en Espagne, Hollande et Grande Bretagne[8)]. En tenant compte de variables telles que la situation socioéconomique et le niveau de formation de la mère, les facultés de mémorisation et de lecture des enfants diminuaient avec l'augmentation du bruit aérien et du trafic à proximité de l'école. Une analyse séparée des données hollandaises a mis en évidence une augmentation du taux d'erreurs dans un test cognitif avec l'accroissement de l'exposition au bruit de la route. Une étude transversale récente comparable effectuée à proximité de l'aéroport de Francfort et comprenant 1'243 élèves entre 7 et 10 ans, a conclu qu'un volume sonore amplifié de 20 dB est associé à un retard de deux mois de l'apprentissage de la lecture[9)].

En résumé, on peut retenir que les études effectuées à ce jour concernant les facultés cognitives des enfants ont constaté une relation négative entre bruit au lieu de scolarisation et le traitement de l'information et du langage, la résolution de problèmes et la capacité de mémorisation. Il existe plusieurs hypothèses sur la manière dont cet effet se produit. Il est par exemple postulé que le stress ou l'expérience d'être exposé impuissant au bruit du trafic engendre chez l'enfant résignation, démotivation et autres troubles du comportement qui se répercutent finalement sur l'apprentissage. D'autre part la perte de motivation de l'enseignant peut altérer la qualité de l'enseignement. De manière plus triviale, le bruit du trafic peut influencer l'intelligibilité de l'enseignant dans la salle de classe et les passages répétés d'avions peuvent occasionner de courtes mais nombreuses interruptions et ainsi nuire à l'enseignement.

Problèmes de comportement et dépressions

Les données empiriques concernant les troubles du comportement et les dépressions de l'enfant dus au bruit ne sont pas nombreuses et partiellement contradictoires[4)]. Une grande étude de cohorte danoise, portant sur 46'940 enfants âgés de sept ans, a montré que pour chaque 10 dB d'augmentation de l'exposition cumulée au bruit au lieu de domicile, l'hyperactivité mesurée au moyen du *«Strengths and Difficulties Questionnaire (SDQ)»,* augmentait significativement de 9%[10)]. Dans une autre étude transversale avec 2'897 enfants âgés de 7 à 11 ans à Barcelone, l'exposition de la salle de classe au bruit de la circulation était associée à un risque élevé de symptômes de déficit d'attention mais pas à un score SDQ élevé. La seule étude longitudinale concernant des troubles du comportement chez l'enfant utilisait les nuisances dues au bruit relatées par les parents comme ersatz de l'exposition réelle au bruit au lieu de domicile. Chez les 1'185 enfants bavarois l'apparition de troubles du comportement entre 5 à 6 et 9 à 10 ans corrélait de manière significative avec les nuisances dues au bruit de la circulation perçues par les parents. Il est intéressant de constater que, contrairement à l'étude espagnole, n'était pas concernée l'hyperactivité mais surtout les sous-échelles SDQ «problèmes émotionnels» et «agressions». Dans l'étude londonienne mentionnée plus haut, les enfants exposés au bruit ne se différenciaient pas des enfants non exposés en ce qui concerne l'anxiété et la tendance à la dépression[6)].

Enfants et nuisances sonores

Il existe un grand nombre d'études concernant la perception subjective de nuisances sonores par l'adulte, montrant que 15% des adultes en Europe et en Suisse se sentent incommodés par le bruit. L'étude RANCH déjà mentionnée est une des rares enquêtes concernant les nuisances sonores pendant l'enfance. Elle montre que le nombre d'enfants qui souffrent de la pollution sonore aérienne augmente de 5.1% avec 50 dB ($L_{Aeq7-23}$) à 12.1% avec 60 dB. Dans l'étude de l'aéroport de Londres, les enfants exposés ont déclaré un degré de nuisance et un niveau de stress dus au bruit aérien plus importants que les non exposés. Ces études indiquent que les enfants se sentent eux-aussi incommodés par le bruit, mais en font moins souvent état que les adultes. La raison expliquant que moins d'enfants que d'adultes soient gênés par le bruit, pourrait être que les enfants ressentent l'effet stressant du bruit mais ne savent pas analyser ce stress et l'attribuer au bruit.

Effets cardio-métaboliques

Les effets du bruit de la circulation routière sur les maladies cardiovasculaires de l'adulte ont été confirmés par de nombreuses études[2)]. Sur la base de sept études longitudinales, une méta-analyse a conclu que toute augmentation de 10 dB du bruit de la circulation routière (L_{DEN}) entraîne une augmentation significative du risque de maladies cardiaques ischémiques de 8%[12)]. Chez l'enfant ont été examinés principalement les modifications de la pression artérielle et de la fréquence cardiaque. L'étude de cohorte PIAMA a comparé la pression artérielle de 1'432 enfants de 12 ans à l'exposition au bruit du trafic, sans constater de relation significative[13)]. Dans l'étude RANCH, l'exposition au bruit d'avions au domicile était associée de manière significative et à l'école de manière non significative à une pression artérielle élevée. Par contre a été observée une corrélation entre augmentation du bruit routier au lieu de l'école et une diminution de la pression artérielle, un constat qui n'a pas trouvé d'explication dans l'étude. Une méta-analyse récente de 13 études avec des enfants n'a pas trouvé de corrélation significative entre pression artérielle et exposition au bruit[14)]. De nombreuses études étaient néanmoins limitées sur le plan méthodologique. Les données contradictoires des rares études pourraient s'expliquer par la plus courte durée cumulative de l'exposition, les effets potentiels escomptés étant donc moindres que chez l'adulte. Même si le bruit n'avait que des effets mineurs sur le système cardiovasculaire de l'enfant, cela pourrait avoir des effets négatifs à long terme sur la santé cardiovasculaire à l'âge adulte.

Plusieurs études de cohortes menées chez des adultes ont mis en évidence que le bruit de la circulation routière est associé avec un risque accru de surpoids ou de diabète[4)]. Dans l'étude de cohorte danoise mentionnée plus haut et portant sur plus de 40'000 enfants, le risque de surpoids à l'âge de 7 ans a augmenté de 6% par 10 dB d'augmentation de l'exposition au bruit de trafic au lieu de domicile pendant la grossesse ou les sept premières années de vie. Ces résultats n'ont été confirmés que partiellement dans une étude norvégienne[15)]. Dans la population de 22'975 enfants étudiée, a été constatée une corrélation négative entre l'exposition au bruit de circulation routière de la maman pendant la grossesse et le BMI de l'enfant à la naissance et, comme dans l'étude danoise, une corrélation positive avec le BMI à 8 ans. Dans l'étude norvégienne l'exposition au bruit de circulation pendant l'enfance n'a par contre pas influencé le BMI.

Sommeil

Outre l'effet de stress, les problèmes de sommeil liés au bruit peuvent également détériorer la santé à long terme, le sommeil ayant une fonction importante pour la santé et le développement de l'enfant qui par ailleurs nécessite des temps de sommeil plus longs. Dans une revue récente sont décrites cinq études concernant l'influence du bruit de la circulation sur le sommeil des enfants[5]. Toutes ces études, effectuées auprès d'enfants entre 7 et 13 ans, mentionnent une corrélation faiblement négative entre exposition au bruit de la circulation et qualité du sommeil décrite par les enfants. Les enquêtes n'étant pourtant pas uniformes en ce qui concerne la durée de sommeil et le niveau d'exposition observé, il n'est pas possible de savoir à partir de quel niveau sonore il faut s'attendre à des effets négatifs sur le sommeil. Une seule de ces cinq études a récolté, par actigraphie, des données objectives concernant la qualité du sommeil[16]. Il n'a pas été observé de corrélation entre l'exposition au bruit de la circulation routière modélisée et la latence (objective) du sommeil ainsi qu'avec les mouvements et les phases de réveil pendant le sommeil. Les auteurs se posent néanmoins la question si l'actigraphie est une méthode adéquate pour mesurer la qualité du sommeil d'un enfant. Trois petites études incluant au total 47 enfants ont évalué l'effet du bruit sur la qualité du sommeil de petits enfants. Dans les trois études, des indices laissent supposer que le bruit affecte la qualité du sommeil aussi des enfants de moins de cinq ans.

Par une analyse ultérieure des données on a essayé de préciser si les effets du bruit aérien sur la cognition, observés dans l'étude RANCH et l'étude de l'aéroport de Munich, ne devaient pas plutôt être attribués aux troubles du sommeil dus au bruit. Les données n'ont toutefois pas permis de confirmer cette hypothèse.

Effets sur l'audition

Outre les effets dus au bruit décrits jusqu'ici et observés lors d'expositions sonores modérées, l'exposition à des bruits intenses représente un facteur de risque pour l'ouïe de l'enfant. Les lecteurs audio sont une source de bruit importants, avec des répercussions potentielles sur l'ouïe. Un bruit très fort (>120 dB) de courte durée ou une exposition plus longue de ≥ 85 dB suffisent à occasionner des dommages. Contrairement aux atteintes aiguës de l'ouïe, les troubles auditifs apparaissant lentement lors d'une exposition chronique ne sont initialement guère perçus, les dangers pour la santé sont donc sous-estimés. Lors d'une enquête, les adolescents semblaient néanmoins être conscients des dangers à long terme causés par une musique trop forte[17]. Cela ne s'est par contre pas nécessairement traduit dans les actes. Dans une étude d'intervention, seulement la moitié des adolescents qui écoutaient leur musique avec un volume élevé ont déclaré, après avoir été informés sur les effets négatifs de cette manière de faire, vouloir à l'avenir écouter la musique plus doucement[17]. Ce n'est pas une constatation très surprenante, mais elle souligne qu'il sera nécessaire d'aborder plus efficacement, avec les adolescents, ce risque pour la santé dû au bruit «souhaité» et basé sur des normes comportementales. Il faut par ailleurs considérer que les écouteurs audio sont souvent utilisés pour s'isoler du bruit environnemental dérangeant.

Que peut faire le médecin contre le bruit?

Dans la pratique médicale quotidienne, l'effet du bruit sur la santé des enfants est un problème difficile à cerner et à quantifier. Comme nous l'avons précisé, le bruit n'est souvent qu'un facteur parmi d'autres, accentuant des symptômes indésirables mais ne se manifestant que rarement par une pathologie pendant l'enfance.

Il se pose donc la question de ce que le médecin traitant peut faire dans ce contexte. D'une part il est utile que les médecins prennent conscience du problème et expliquent aux patients que les nuisances sonores ne sont pas seulement «exaspérantes» pour l'enfant aussi, mais peuvent occasionner, à court ou long terme, des troubles somatiques ou psychiques. Lors de consultations touchant à l'hyperactivité, à des troubles du comportement ou du sommeil, à la fatigue ou aux difficultés scolaires, le bruit devrait dans tous les cas être évoqué par le médecin. Les parents devraient être sensibilisés afin de réfléchir aux moyens permettant de minimiser l'exposition au bruit de la famille et surtout des enfants.

Possibilités concrètes pour aborder le problème du bruit dans le quotidien de l'enfant:

- Quelle est la situation concernant les bruits extérieurs (p.ex. avions, train)? Existent-ils des moyens pour s'en protéger? Est-ce que la chambre d'enfant se situe du côté d'une rue silencieuse?
- Quelles sont les sources de bruit potentielles la nuit? Lorsque les parents se trouvent dans la chambre à côté, quelle est l'intensité des bruits dans la chambre d'enfant?
- Est-ce que les voisins sont bruyants et passent des soirées animées? Est-ce que ces bruits peuvent être limités en communiquant avec les voisins et en changeant l'affectation des pièces?
- Est-ce qu'il y a des bruits dans le ménage qui peuvent être réduits? Est-ce qu'il y a constamment un téléviseur allumé ou de la musique?
- Est-ce que dans une famille avec de nombreux enfants il y a des lieux – havres de paix – où ils peuvent se retirer?
- Le bruit occasionné par des jouets peut être testé lors de l'achat. On peut fixer en commun les règles pour les jouets bruyants et introduire des moments de silence, notamment lors du coucher.
- Est-ce que les enfants connaissent les dangers de la musique forte écoutée avec des lecteurs audio? Sont-ils conscients que la musique ne devrait pas être trop forte? Est-ce que des règles ont été fixées pour que les lecteurs audio ne soient pas utilisés en permanence et qu'il y ait des plages de silence?

Le médecin peut aborder le sujet bruit à l'hôpital ou au cabinet. Il est connu que la qualité du sommeil des patients est moins bonne dans les hôpitaux. Un facteur important qui contribue à une moins bonne qualité du sommeil est le bruit occasionné par les appareils, les soignants et les autres patients. Les mesures effectuées dans des chambres d'hôpital ont montré que l'exposition moyenne au bruit dépassait les 50 dB, dans certains cas même les 60 dB[5]. L'OMS recommande pour les cliniques un niveau sonore de 40 dB dans les couloirs et de 30 dB dans les chambres des patients. Il est aussi recommandé de fixer des plages de silence, pendant lesquelles les soignants, les visiteurs et les patients sont priés de ne pas faire de bruit. Pour sensibiliser les soignants, les visiteurs et les patients au problème du bruit excessif, on peut installer des témoins lumineux qui indiquent un dépassement de la limite sonore prévue.

Références

1) Rice JB. In an Effort to Suppress Noise. The Forum 1906;37.
2) Münzel T, Sørensen M, Gori T, Schmidt FP, Rao X, Brook J, et al. Environmental stressors and cardiometabolic disease: part I-epidemiologic evidence supporting a role for noise and air pollution and effects of mitigation strategies. European heart journal. 2017;38(8):550-6.

3) Evans GW, Bullinger M, Hygge S. Chronic noise exposure and physiological response: A prospective study of children living under environmental stress. Psychological science. 1998;9(1):75-7.
4) Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S, et al. Auditory and non-auditory effects of noise on health. Lancet. 2014;383(9925):1325-32.
5) Basner M, McGuire S. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep. International journal of environmental research and public health. 2018;15(3):519.
6) Haines MM, Stansfeld SA, Job RS, Berglund B, Head J. A follow-up study of effects of chronic aircraft noise exposure on child stress responses and cognition. International Journal of Epidemiology. 2001;30:839-45.
7) Hygge S, Evans GW, Bullinger M. A prospective study of some effects of aircraft noise on cognitive performance in schoolchildren. Psychological science. 2002;13(5):469-74.
8) Stansfeld SA, Berglund B, Clark C, Lopez-Barrio I, Fischer P, Öhrström E, et al. Aircraft and road traffic noise and children's cognition and health: a cross-national study. The Lancet. 2005;365(9475):1942-9.
9) Klatte M, Spilski J, Mayerl J, Möhler U, Lachmann T, Bergström K. Effects of aircraft noise on reading and quality of life in primary school children in Germany: Results from the NORAH study. Environment and Behavior. 2017;49(4):390-424.
10) Hjortebjerg D, Andersen AMN, Christensen JS, Ketzel M, Raaschou-Nielsen O, Sunyer J, et al. Exposure to road traffic noise and behavioral problems in 7-year-old children: A cohort study. Environmental health perspectives. 2016;124(2):228.
11) Van Kempen EE, Van Kamp I, Stellato RK, Lopez-Barrio I, Haines MM, Nilsson ME, et al. Children's annoyance reactions to aircraft and road traffic noise. The Journal of the Acoustical Society of America. 2009;125(2):895-904.
12) Van Kempen EE, Casas M, Pershagen G, Foraster M. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cardiovascular and Metabolic Effects: A Summary. International journal of environmental research and public health. 2018;15(2):379.
13) Bilenko N, Rossem Lv, Brunekreef B, Beelen R, Eeftens M, Hoek G, et al. Traffic-related air pollution and noise and children's blood pressure: results from the PIAMA birth cohort study. European journal of preventive cardiology. 2015;22(1):4-12.
14) Dzhambov, AM., Dimitrova, DD. Children's blood pressure and its association with road traffic noise exposure–A systematic review with meta-analysis. Environmental research, 2017; 152:244-255.
15) Weyde KV, Krog NH, Oftedal B, Magnus P, White R, Stansfeld S, et al. A longitudinal study of road traffic noise and body mass index trajectories from birth to 8 years. Epidemiology. 2018.
16) Öhrström E, Hadzibajramovic E, Holmes M, Svensson H. Effects of road traffic noise on sleep: Studies on children and adults. Journal of environmental psychology. 2006;26(2):116-26.
17) Martin WH, Martin W, Griest SE, Lambert W. How loud is your music? Beliefs and practices regarding use of personal stereo systems. 33rd Annual Hearing Conservation Conference of the National Hearing Conservation Association Portland, Oregon; 2008.

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3.3 English Version

How does noise affect children?

Introduction

Noise and its effects have been around for a long time, as something people cared about. It is reported that in ancient Rome carriage traffic in the city center was restricted, with the intention to reduce unwanted noise. With the start of industrialization in the second half of the 18th century, engines and machines increasingly contributed to noise pollution in the cities - which people in the cities began to resist even then.

Julia Barnett Rice, wife of a wealthy businessman in New York City, protested in 1906 against the noise produced by the noisy tugboat signal horns in Hudson Bay. She wrote an article titled: «In an Effort to Suppress Noise». She interviewed various people affected by the problem topic and argued even at that time based on the expert opinion of a Dr. John H. Girdner of a hospital near the Bay who noted that children are particularly sensitive to noise:

«City noises exert a deleterious effect on the human system; this is especially marked in the case for invalids and children. Noise is a most potent factor in producing functional diseases of the brain and nervous system, not alone by its direct action, but by destroying sound, refreshing sleep.» (Rice, 1906)

In Germany, Theodor Lessing wrote a book in 1908 entitled: «A right to Silence"; he subsequently founded the first "Anti-Noise Association".

But what actually is noise, particularly unwanted noise? Everyone is exposed to noise every day. But when does noise turn into unwanted noise? There is no strict scientific definition of noise. In general, 'noise' is described as unwanted sound. The most common source of noise, and also the most researched noise is traffic noise, as produced on streets, or by trains or air traffic. Other frequently mentioned sources of disturbing noise are construction and industrial noise, noise produced in the neighborhood (loud music, noisy household appliances), ringing church bells or other noise resulting from leisure activities.

The sound pressure level of noise is measured using the decibel (dB) scale. In addition to the mean value of noise impact (L_{Aeq}), noise impact research also uses the time-weighted average L_{den} (Day-Evening-Night). In this measure, 5 or 10 dB are added to evening and night hours, respectively, to take into account that noise might affect health more at night than during the day.

What is the impact of chronic noise pollution on health?

The German word for noise is "Lärm" - which derives from the Italian "all'arme" (to arms), illustrating the permanent alert, or stress response which noise can produce in humans. Physiologically, this stress reaction consists of the activation of both the sympathetic nervous system as well as of the hypothalamus-pituitary-adrenal axis, also called stress axis (Münzel et al., 2017). One of the few studies looking at the hormonal reaction to stressful noise in children found significant increases in the levels of adrenalin and noradrenalin in children aged around 10 years living near the newly opened Munich airport (Evans et al., 1998).

A chronic level of stressful noise can have a variety of negative effects on health in the long term. Important contributing factors are the type of noise, as well as the situation and predisposition of affected individuals. The most well-known health problems associated with noise in adults are annoyance, poor sleep, impact on the cardiovascular system and on the metabolism as well as on mental health (Basner et al., 2014).

The negative impact of noise on child health has received much less attention to date, even though it is argued that children are especially sensitive to noise because they are still in a phase of development and growth. Children go to bed earlier and sleep longer, and therefore experience longer periods of noise exposure and potential disruptions of sleep (Basner & McGuire, 2018).

Impact on the cognitive capacity of children

The most studied health effects from chronic noise on children are impairments of cognitive capacities, such as ability to read, memory performance, or attention span; these effects have often been studied in schools exposed to flight noise due to a proximity to airports.

A first longitudinal study was carried out in 2001 in England in 275 children aged eight to eleven years of age (Haines, Stansfeld, Job, et al., 2001). This study compared reading comprehension and attention span between children near a London airport with a control group not exposed to airport noise; the assessment was repeated 10 years later. Cross-sectional analyses, controlling for age, socio-economic status and mother tongue showed that reading skills and ability to concentrate in noise-exposed children were significantly lower compared to non-exposed children. In longitudinal analyses, largely similar associations were seen for development of reading skills and ability to concentrate over one year; these associations were not statistically significant, however. The study also tested the hypothesis that children might get used to noise within one year, but could not find evidence supporting this hypothesis.

Another prospective cohort study with 326 children conducted in Munich took advantage of the fact that the old Munich airport was closed while the new airport was opened at the same time (Hygge et al., 2002). Four groups of children with the same average age (10 yrs) and socioeconomic status, were examined. Two of these groups lived near the old airport, the other two resided near the new airport, with one of the two groups in each area exposed to flight noise, and the other not exposed. All children were examined once before the airport change-over, and twice after the change-over. Children exposed to flight noise near the old airport showed reduced long-term memory and reduced reading comprehension at the time of the first examination (when the old airport was still in operation), compared to non-exposed children. This difference had largely disappeared two years after the old airport was closed. Similarly, reduced memory performance and reading comprehension was observed in flight-noise exposed children living near the new airport, compared to the non-exposed control group.

These results are consistent with the large international cross-sectional study "RANCH", which included 2844 nine to ten year old children from 89 different schools near airports in Spain, the Netherlands and Great Britain (Stansfeld et al., 2005). Taking into account confounders such as socioeconomic status and maternal education, reading ability and memory performance of school children decreased with increasing aircraft and road noise on school premises.

A separate analysis of the Dutch data found an increasing error rate in a cognitive test among children as the level of street noise children were exposed to increased. A new similar cross-sectional study conducted examining 1243 school children from 7 to 10 years of age in the area around Frankfurt Airport concluded, that a 20 dB higher noise level was associated with a delay of two months in reading skill development in exposed children (Klatte et al., 2017).

In conclusion, the studies assessing the impact of noise on the cognitive capacity of children have mainly found negative associations of noise near the location of schools with processing of information and understanding of language, as well as with problem solving and memory skills. Several hypotheses exist as to the way in which these effects may occur. It has been postulated that the stressful effect of noise or the experience to be powerless vis-a-vis the exposure to noise has led children to resign, feel demotivated and develop other behavioral problems, all of which will have negative impact on learning ability. In addition, noise-induced negative impact on the motivation of teachers may reduce a teacher's teaching performance. Also, constant traffic noise may simply decrease the audibility of what teachers say, or frequent flyover of jet planes cause frequent interruptions of lessons.

Behavioral problems and depression

There is a shortage of empiric data on the association of noise pollution with behavioral problems and depression in children; some of the existing data is contradictory (Basner et al., 2014). A large Danish cohort study of 46940 seven-year olds revealed that the level of hyperactivity, measured with the 'Strengths and Difficulties Questionnaire (SDQ)', increased by 9% for every 10 dB rise in cumulative noise exposure (Hjortebjerg et al., 2016).

Another cross-sectional study involving 2897 seven to eleven-year old children in Barcelona showed that classroom exposure to traffic noise was associated with an increased risk of attention deficit syndrome, but not with an increased SDQ score. The only longitudinal study on behavioral problems in children utilized the parent-reported noise annoyance as a surrogate for the actual noise pollution at the child's residence. In this study the occurrence of new behavioral problems in the 1185 Bavarian children between the 5./6. and the 9./10. year of life was significantly associated with the parental traffic noise annoyance. Interestingly, this study did not report an association with hyperactivity, but mainly with the SDQ sub-scales of 'total difficulties', 'emotional problems' and 'conduct problems'.

The study of children near a London airport discussed earlier did not find any difference between children exposed or not exposed to noise related to levels of anxiety or tendency towards depression (Haines, Stansfeld, Job, et al., 2001).

Noise annoyance in children

Numerous studies on noise annoyance in adults have shown that around 15% of adults in Europe and Switzerland feel bothered by chronic noise pollution. The RANCH study discussed above is one of the few assessments of level of noise annoyance in children. The RANCH study found that the proportion of children who feel disturbed by flight noise increases from 5.1% at 50 dB to 12.1% at 60 dB (van Kempen et al., 2018). Likewise, the London airport study found that the degree of disturbance and self-reported stress level was higher in noise-exposed children compared to children not exposed to noise. These study results indicate that children do also perceive noise as disturbing, but to a lesser degree compared to adults. One reason for this difference may be that children do experience noise as a stressor, but that they are not yet able to analyze the situation or link the stressful situation back to the noise exposure.

Cardio-metabolic effects of noise in children

The negative impact of traffic noise pollution on cardio-vascular disease in adults have been confirmed in a number of studies. A meta-analysis of seven longitudinal studies concluded that there was a significant 8% increase of ischemic heart disease for every 10 dB increase in traffic noise (van

Kempen et al., 2018). Studies in children have mainly assessed changes in blood pressure and heart rate. The PIAMA cohort study assessed blood pressure in 1432 12-year old children in relation to their exposure to traffic noise, without finding any statistically significant association (Bilenko et al., 2015). In the RANCH study, the association of flight noise exposure with increased blood pressure was significant for children exposed to flight noise at home, but not significant for children exposed to flight noise at school. In fact, the RANCH study unexpectedly found a significant association between flight noise exposure at school and decreasing blood pressure, which could not be explained in the study.

A more recent meta-analysis of 13 studies in children did not find a significant association between blood pressure and exposure to noise (Dzhambov & Dimitrova, 2017); however, several of these studies had methodological limitations. The contradictory findings of this limited number of studies may be caused in part by the shorter cumulative duration of exposure to noise in children, which could be expected to result in smaller potential effect, compared to adults. Even if the impact of noise on the cardio-vascular system of children was only weak, this may still translate to considerable long-term negative impact on cardiovascular health in adults.

Several cohort studies in adults found that traffic noise was associated with an increased risk of overweight and diabetes (Basner et al., 2014). The Danish cohort study of more than 40.000 children referred to above found that the risk of being overweight increased by 6% for every 10 dB increase in street traffic noise exposure near the child's residence; the association was the same for the period of pregnancy (i.e. pre-natally) or for the first 7 years of life. These results could only partially be confirmed in a recent Norwegian study, in which 22.975 children were enrolled (Weyde et al., 2018). In this study, a negative association was found between street traffic noise exposure of the mother during pregnancy and the BMI of the baby at birth; however, the association was positive with the BMI of children at 8 years of age, similar to the Danish study. In the Norwegian study, no impact was found between street traffic noise exposure during childhood and BMI.

Sleep

In addition to noise acting as a stressor per se, noise-related impact on sleep can affect health in the long term; sleep has an important function for the well-being and development of children, who require a longer period of sleep compared to adults. A recent review paper describes the findings of five studies on the impact of traffic noise on the quality of sleep in children (Basner & McGuire, 2018). All studies of children aged between seven and thirteen years found weak associations between street traffic noise and self-reported quality of sleep. However, these studies differ in relation to the metrics used to assess quality of sleep and noise exposure, which does not allow to deduct from which level of noise exposure negative effects on sleep quality can be expected. Only one of these five studies collected additional objective data data from 80 children on sleep quality, using actigraphy, a non-invasive method of monitoring human rest/activity cycles (Öhrström et al., 2006). These data did not reveal an association between modeled street noise exposure and objectively measured latency of sleep, as well as movements and periods of being awake. The study did, in fact, question whether or not actigraphy constituted a good way to measure sleep quality in children.

Three smaller studies with a combined total of 47 enrolled children examined the effects of noise in the hospital on toddlers. All three studies claim to have found evidence that noise negatively impacts the quality of sleep even in children under 5 years of age.

An analysis following up the RANCH and Munich airport study, an attempt was made to clarify to what extent the observed effects of flight noise on the cognitive capacity of children might have also resulted from noise-induced negative impact on sleep quality; however, this could not be confirmed based on the data available.

Hearing

In addition to the impact of noise described so far, some of which can be observed already with moderate exposure to noise in the environment, exposure to high levels of noise represent a risk factor affecting the auditive capacity of children. In this context, audio player are an important source of noise with potential effect on a child's hearing. Potential damage can be caused already by short exposure to very high levels of noise (> 120 dB), or exposure to 85 dB or higher for longer periods. In contrast to acute hearing damage, damage developing gradually due to chronic noise exposure may not even be noticed initially, which leads to under-estimating the related negative health effects. Nevertheless, adolescents responding to a survey seemed to be aware of the long-term risk due to listening to overly loud music (Martin et al., 2008). This awareness unfortunately did not necessarily lead to corresponding action. Only about half of the adolescents enrolled in an interventional study who were informed in detail about the negative impact of listening to music at high levels of loudness voiced their intention to listen to their favorite music at lower levels of loudness in the future (Martin et al., 2008). This finding is not surprising but underlines that it will be important in the future to better address and mitigate this behavior-based health risk through 'desired noise' in adolescents. In this context, it is important to note that audio players with headphones are often used to keep out environmental noise. Therefore, there is an interaction of these two sources of noise with potentially negative impact.

What can be done in the pediatric practice to reduce noise-related risks in children?

The negative impact of noise on child health is a problem that is not easy to define, detect or quantify. As discussed, noise often is just one factor among others, which may amplify undesired symptoms, but will only rarely lead to manifest illness in children.

This leaves the question what action, if any, a pediatrician can do to mitigate this specific risk. On the one hand, it is helpful if physicians and pediatricians become aware of the problem, and begin in turn to sensitize and alert the caretakers of their patients about the fact that unwanted noise is not only stressful for children but can have somatic and psychological effects on children over the short and long term. Questions and a discussion about possible noise exposure should be part of history-taking in any child presenting with hyperactivity, behavioral problems, sleep disturbance, fatigue and school problems. Caretakers should be sensitized accordingly, including to consider options how the level of noise a family, and particularly children, may be exposed to may be minimized.

Concrete options to discuss the noise exposure of children

Is there a source of external noise, i.e. airport / flight noise or noise emanating from rail traffic? Are there options to shield the family / a child from such exposure? Is there an option to have the child's room face a quiet street?

Are there potential sources of noise during the night? With parents sitting or talking in a room next to the child's room, how audible is the conversation, or the sound of the TV / radio, in the child's room?

Are there neighbors in adjacent apartments who have frequent guests and social interactions up to the late hours of the evening? Could this noise exposure potentially be reduced through communicating with and explaining the situation to the neighbors?

Are there sources of noise in the household which could be reduced? Is there an 'always on' TV set or radio producing constant background noise?

In households with multiple children, are there 'quiet places' where children can retreat to?

The potential of a toy to emit noise should be assessed before the toy is purchased. Rules for playing with noise-emitting toys can be set jointly with the child, and 'quite time' be established, particularly before bed-time.

Are older children and adolescents aware of the risks of listening to music and audio material at high volume levels, particularly when listening to music using audio-players and headphones? Are they aware that music should not be played at volumes beyond a certain preset volume level? Have rules been established to make sure audio-players are not used permanently, and that there need to be periods of 'quite time'?

Doctors and other health workers should make sure that the topic of noise pollution should be addressed in hospitals and daily clinical routine. It is quite well-known that the quality of sleep for many hospitalized patients is reduced. An important contributing cause is the noise generated by medical devices, hospital staff, and other patients. Measurements of the level of noise in hospital rooms have shown that the mean level of noise in hospital rooms exceeded 50 dB, and was above 60 dB in particular cases (Basner & McGuire, 2018). WHO recommends that noise hospitals should not exceed 40 dB in hallways and 30 dB in patient rooms. It is also recommended to establish 'quiet times' in health facilities during which health workers, visitors and patients are requested to maintain silence. One option to sensitize health workers, visitors and patients about the problem of excessive noise is to make use of specially developed lights which light up to indicate when a pre-determined level of noise has been exceeded.

References

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014, 10/30). Auditory and non-auditory effects of noise on health. *Lancet, 383*(9925), 1325-1332. https://doi.org/10.1016/S0140-6736(13)61613-X

Basner, M., & McGuire, S. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep. *International Journal of Environmental Research and Public Health, 15*(3), 519.

Bilenko, N., Rossem, L. v., Brunekreef, B., Beelen, R., Eeftens, M., Hoek, G., Houthuijs, D., De Jongste, J. C., Kempen, E. v., & Koppelman, G. H. (2015). Traffic-related air pollution and noise and children's blood pressure: results from the PIAMA birth cohort study. *European journal of preventive cardiology, 22*(1), 4-12.

Dzhambov, A. M., & Dimitrova, D. D. (2017). Children's blood pressure and its association with road traffic noise exposure–A systematic review with meta-analysis. *Environmental research, 152*, 244-255.

Evans, G. W., Bullinger, M., & Hygge, S. (1998). Chronic noise exposure and physiological response: A prospective study of children living under environmental stress. *Psychological science, 9*(1), 75-77.

Haines, M. M., Stansfeld, S. A., Job, R. S., Berglund, B., & Head, J. (2001). A follow-up study of effects of chronic aircraft noise exposure on child stress responses and cognition. *International Journal of Epidemiology, 30*, 839-845.

Hjortebjerg, D., Andersen, A. M. N., Christensen, J. S., Ketzel, M., Raaschou-Nielsen, O., Sunyer, J., Julvez, J., Forns, J., & Sørensen, M. (2016). Exposure to road traffic noise and behavioral problems in 7-year-old children: A cohort study. *Environmental health perspectives, 124*(2), 228.

Hygge, S., Evans, G. W., & Bullinger, M. (2002). A prospective study of some effects of aircraft noise on cognitive performance in schoolchildren. *Psychological science, 13*(5), 469-474.

Klatte, M., Spilski, J., Mayerl, J., Möhler, U., Lachmann, T., & Bergström, K. (2017). Effects of aircraft noise on reading and quality of life in primary school children in Germany: Results from the NORAH study. *Environment and Behavior, 49*(4), 390-424.

Martin, W. H., Martin, W., Griest, S. E., & Lambert, W. (2008). How loud is your music? Beliefs and practices regarding use of personal stereo systems. 33rd Annual Hearing Conservation Conference of the National Hearing Conservation Association. Portland, Oregon,

Münzel, T., Sørensen, M., Gori, T., Schmidt, F. P., Rao, X., Brook, J., Chen, L. C., Brook, R. D., & Rajagopalan, S. (2017). Environmental stressors and cardio-metabolic disease: part I–epidemiologic evidence supporting a role for noise and air pollution and effects of mitigation strategies. *European heart journal, 38*(8), 550-556.

Öhrström, E., Hadzibajramovic, E., Holmes, M., & Svensson, H. (2006). Effects of road traffic noise on sleep: Studies on children and adults. *Journal of Environmental Psychology, 26*(2), 116-126.

Rice, J. B. (1906, 1906). In an Effort to Suppress Noise. *The Forum 37*.

Stansfeld, S. A., Berglund, B., Clark, C., Lopez-Barrio, I., Fischer, P., Öhrström, E., Haines, M. M., Head, J., Hygge, S., & Van Kamp, I. (2005). Aircraft and road traffic noise and children's cognition and health: a cross-national study. *The Lancet, 365*(9475), 1942-1949.

van Kempen, E., Casas, M., Pershagen, G., & Foraster, M. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cardiovascular and Metabolic Effects: A Summary. *International Journal of Environmental Research and Public Health, 15*(2), 379.

Weyde, K. V., Krog, N. H., Oftedal, B., Magnus, P., White, R., Stansfeld, S., Øverland, S., & Aasvang, G. M. (2018). A longitudinal study of road traffic noise and body mass index trajectories from birth to 8 years. *Epidemiology*.

4 The association of road traffic noise with problem behaviour in adolescents: a cohort study

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The association of road traffic noise with problem behaviour in adolescents: A cohort study

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ABSTRACT

The findings of environmental noise exposure and behavioural disorders in children and adolescents are inconclusive, and longitudinal studies are scarce. We studied the response of behaviour and behavioural change within one year in a cohort of 886 adolescents in Switzerland aged 10–17 years in response to road traffic noise exposure.

Participants filled in a comprehensive questionnaire at baseline and follow-up. It included the Strengths and Difficulties Questionnaire (SDQ), which measures self-rated positive and negative behaviours in five scales. We modelled road traffic noise for participants' most exposed facade at home and school addresses in various metrics (L_{den}, L_{night}, L_{day}, Intermittency Ratio and Number of events). We addressed missing data with multiple imputation and performed mixed linear cross-sectional analyses and longitudinal change score analyses.

In cross-sectional analyses, peer relationship problems increased by 0.15 units (95%CI: 0.02, 0.27; scale range: 0–10) per 10 dB road traffic noise increase. In longitudinal analyses, increases in SDQ scales between baseline and follow-up were not related to noise exposure.

This study suggests subtle associations between road traffic noise exposure and behaviour problems in adolescents, but longer follow-up times may be needed to observe longitudinal changes.

1. Introduction

Noise can affect health acutely or chronically, leading to a variety of health issues, such as reduced quality of sleep, stress, cardiovascular diseases, and alteration of the cognitive functions. Children are considered at particular risk of negative health consequences due to noise (WHO, 2009). The European Environmental Agency estimates that in Europe environmental noise resulted in 453,000 Disability Adjusted Life Years (DALYs) in 2017 from high noise annoyance, 437,000 from sleep disturbance, 156,000 from heart disease and 75 from cognitive impairment in children (Peris, 2020). They further conclude that 12,500 children aged 7 to 17 are affected by aircraft noise induced reading impairment. The EEA does not consider potential effects on the behaviour of children and adolescents due to limited and inconclusive study results.

The Strength and Difficulties Questionnaire (SDQ), the most frequently used outcome measurement tool, has five different dimensions representing various aspects of behaviour. This adds to the complexity and heterogeneity as different studies report associations for some dimensions and not others. For example, a study of 46,940 children aged 7 showed a significant higher hyperactivity/inattention in children exposed to more road traffic noise, and significantly more peer problems and more total difficulties associated with railway noise (Hjortebjerg et al., 2016). On the other hand, another study with 2014 children, aged 9–10 years in the UK, Spain and the Netherlands showed an association of hyperactivity/inattention with aircraft noise, and

Abbreviations: Bedroom orientation, bedroom orientation towards loudest street by the house; ARTN, adjusted road traffic noise; IR, Intermittency Ratio; N_{evt}, Number of events.

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decreased conduct problems in relation to road traffic noise (Stansfeld et al., 2009). A recent systematic review and meta-analysis based on three included studies concluded that the hyperactivity/inattention score significantly increased by 11% (95% Confidence Interval: 4%, 19%) per 10 dB road traffic noise exposure (Schubert et al., 2019), while total behavioural difficulties increased by 9% (95%CI: 2%, 16%) per 10 dB.

So far, only two studies considered the change in behavioural outcome over time in relation to noise exposure. The first, on noise annoyance of parents – used as a proxy for noise exposure – showed a positive association with changes in the total difficulties score, emotional problems, conduct problems and peer relationship problems after 4 years in children aged 5–6 years at baseline (Dreger et al., 2015). As noise annoyance might represent more than noise exposure levels (e.g. also aspects related to perception of noise, mental health, stress and resilience), the results of this study are subject to considerable uncertainty in relation to the associations of modelled noise exposure with behavioural outcomes. A more recent cohort study of 1546 Brazilian children, aged three to six years, found an increase in the SDQ score in relation to noise (Raess et al., 2022). In this study, community noise exposure, assessed by means of a land use regression model that incorporated measurements from roads, schools, greenness, residential and informal settlements, was high (mean L_{den}: 70.3 dB and mean L_{night}: 61.2 dB).

In previous studies, noise exposure is either measured or modelled at schools (Clark et al., 2012; Haines et al., 2001; Stansfeld et al., 2009), or at home (Hjortebjerg et al., 2016; Tiesler et al., 2013; Weyde et al., 2017). Only a few studies have considered both together, which may more accurately represent noise levels that children are exposed to over the whole day. In a Bulgarian study of 311 children aged 7–11, equivalent noise levels over 24 h were measured at home and at school (Belojevic et al., 2012). This study did not show any overall relationship of road traffic noise at home or school levels with hyperactivity, except for a significant association of road traffic noise at home with hyperactivity only in boys. A recent study in 229 Dutch children aged 11 years combined road traffic noise exposures of both home and school in one model and found an unexpected negative relationship with ADHD diagnosis, while not showing any association with ADHD severity (Zijlema et al., 2021).

Another reason for differences between study results could be the choice of noise metric. Most studies used the day-evening-night equivalent level (L_{den}), which adds a respective 5 and 10 dB penalty to evening and night noise to reflect the stronger health impacts during those more sensitive times. It could be that in addition to the average level, individual noise events (e.g. quantified by number of events (N_{evt})) are more stressful and have strong impacts. Wunderli et al. (2016) further proposed to capture eventfulness of noise normalised to the average sound pressure level by the Intermittency Ratio (IR). An IR of more than 50% indicates that “distinct” noise events make up more than half of the total sound energy. Including IR in an epidemiological model adds a further dimension, showing not only how transportation noise levels or individual noise events affect health, but also how the difference between them might have shown independent associations with the outcome.

Noise models usually refer to the most exposed façade. Babisch et al., 1999 showed that using a correction of the noise exposure variable (the bedroom orientation towards loudest street by the house (abbr.: ‘bedroom orientation’) and ‘window open/closed’) increased an association between road noise and ischemic heart disease, though both analyses stayed non-significant at the 5% level. Foraster et al. used information on the bedroom orientation to deduct 20 dB from modelled noise to portray realistic noise exposure inside the bedroom (Foraster et al., 2014). Brink et al. (2019) showed that bedroom orientation was an important effect modifier of the relationship between modelled road traffic noise and high sleep disturbance.

The research to date has not been able to provide robust evidence for the relationship between noise exposure and behaviour in adolescents. This is due to different methodologies, different metrics used for exposure assessment, and the fact that there are few longitudinal studies available. Further, the current evidence shows overall mixed findings of the six SDQ psychological attributes.

The objective of this study therefore was to determine how road traffic noise may affect behaviour outcomes in adolescents by controlling the following aspects: We took into account noise exposure at home and school and explored different noise metrics (L_{den}, $L_{night/day}$, N_{evt}, IR). We also considered bedroom orientation and window opening habits, and adjusted for risk factors confounding by the education level of parents as a proxy for socioeconomic status. We conducted cross-sectional and longitudinal analyses to evaluate how modelled noise exposure by participant was associated with their behaviour, as well as whether the noise exposure was associated with individuals’ changes in behavioural scores over one year. Our hypothesis was that both hyperactivity/inattention and possibly total difficulties would be heightened related to exposure to road traffic noise exposure, with most pronounced associations for hyperactivity/inattention.

2. Methods

2.1. Sampling and design

This study is based on a prospective cohort study conducted in Switzerland among adolescents called HERMES (Health effects related to mobile phone use in adolescents). The primary objective of the HERMES cohort was to measure the impact of radiofrequency electromagnetic fields on behaviour, quality of life and cognitive functions in adolescents. Participants were recruited in schools in Central Switzerland and Basel.

There were two waves of data collections with two cohorts of participants (1. cohort: N = 442; 2. cohort: N = 457). Both cohorts were subject to the same measurements with a baseline and a follow-up and a year in between measurements (cohort 1 baseline: 2012/13, follow-up: 2013/14; cohort 2 baseline: 2014/15, follow-up:2015/16). These two cohorts were subsequently combined into one (N = 899). For study participant recruitment, the researchers contacted school directors, who informed class-teachers. If both agreed, an informal visit of the class was conducted by a research team to distribute study information material including informed consent sheets for students and parents. For those agreeing to participate, data was subsequently collected during school hours. In addition, parents filled in a questionnaire at home, which they sent back by postal mail. One year later, the same students were revisited for participation in the follow-up, and those that agreed filled in the second questionnaire.

2.2. Outcome

The Strength and Difficulties Questionnaire (SDQ) (Goodman, 1997) is a widely used psychopathological broad-band screening tool for children and adolescents (3–16 years of age) and has been recommended for the German speaking population (Becker et al., 2018). The SDQ consists of five psychological attribute, each comprising five items that are answered on a 3-point Likert scale (‘not true’, ‘somewhat true’, ‘certainly true’). Four of the five psychological attributes are negative: *emotional problems*, *conduct problems*, *hyperactivity/inattention problems, peer relationship problems* and one is positive: *prosocial behaviour* (range for all psychological attributes: 0–10). The four negative attributes are added up into the *total difficulties score* (range: 0–40). Higher scores show more difficulties, or strengths respectively. In the main analysis, we used scores in a continuous form, which were more sensitive to any changes (positive or negative) compared to a categorical or dichotomous outcome (Clark et al., 2013; Weyde et al., 2018). We also used a categorized version of the data for descriptive statistics (in Table 2), as well as in a sensitivity analysis (in supplement table S5) with cut-off points for normal, borderline or severe behaviour in children (Becker et al., 2018). These cut-off points are recommended for a representative German sample and are described in supplement table S1 (see Table 3a-d).

2.3. Covariates

Confounders were the education level of parents (no education, mandatory school, training school "Berufslehre", secondary school "Gymnasium", college of higher education "Fachhochschule", university). Explanatory variables were age (continuous), sex (m/f), education level of participants (Secondary school C to A, Gymnasium), whether participants indicated to drink alcohol (yes/no) or to smoke (yes/no), physical activity (1–3x/month, 1x/week, 2–3x/week, 4–6 x/week, every day), screen time (continuous in minutes) and nationality (both parents Swiss, one parent Swiss, no Swiss parent. Additional variables for sensitivity analyses were bedroom orientation towards loudest street by the house (yes/no), road traffic noise annoyance (annoyed/not annoyed), sensitivity to noise (continuous, range: 0–27) and window open during sleep (always closed/open during summer or winter/always open). The covariates 'bedroom orientation towards loudest street' and 'window opened' were added to the analyses to account for the fact that the assessed noise exposure (see Section 2.4) refers to the most exposed façade only. Road traffic annoyance was collected with a 4-point verbal Likert scale: 'Are you annoyed by road traffic noise?' The answers 'somewhat true' and 'certainly true' were dichotomized as 'annoyed', 'not true at all' and 'not completely true' were dichotomized as 'not annoyed'. Noise sensitivity was collected with a German version of the Weinstein scale, which consists of 9 items with 4 point Likert scale (very true, somewhat true, somewhat untrue, very untrue) (Zimmer and Ellermeier, 1998). Coded from 0 to 3, the scores of these items where then added to a total, resulting in a continuous variable, which was subsequently used without further changes. Following previous studies in the same cohort (Foerster et al., 2018; Roser et al., 2016), we used the difference in height between baseline and follow-up (cm) as a proxy for puberty in the longitudinal analysis. PM_{10} (see section 2.4) was included as an additional covariate and is described in the noise and environmental exposures paragraph.

2.4. Noise and environmental exposures

This study focuses on road traffic noise exposure because the cohort was predominantly exposed to road traffic noise and negligible amount of participants experienced rail of aircraft noise. However, exposure data for all sources (road traffic, railway, aircraft noise) were obtained, with data deriving from the SiRENE study data (Héritier et al., 2017; Karipidis et al., 2014). For each building in Switzerland, road traffic noise for year 2011 was computed via the propagation model of StL-86, railway noise using the Swiss railway noise model SEMIBEL (BAFU, 2009). Aircraft noise was calculated for the three major Swiss airports, as well as for the military airfield in Payerne (Empa, 2010; Pietrzko and Hofmann, 1988). Aircraft noise for civil airports was calculated using radar data and air traffic data, with acoustic footprints per aircraft type and route. For the military airfield, noise was calculated by means of idealized flight paths, operation times and number of flights. We extracted L_{den}, L_{eq} for night and day (L_{night}, L_{day}), IR and N_{evt} for each transportation noise source at the loudest façade point on the participants' homes and their school location. If known, we used the façade point of the participants' dwellings floors; else, we used the first floor of the building.

We manually corrected noise exposure of 50 participants because these participants lived in buildings built after the noise map was designed. These individuals were first identified as having a distance >20 m between the address geocode and existing building in the noise database, and verified via visual inspection of the address and façade points overlaid on up-to-date road and buildings base maps by SwissTopo (map.geo.admin.ch). The corrected values were derived by adding or subtracting 3 dB per doubling or halving of the distance from modelled to new location of participants' dwellings depending on the distance from the road. For 20 participants who moved location between baseline and follow-up, we calculated time-weighted means to describe the participants' mean exposure to noise.

L_{den} noise levels below a threshold of 35 dB (road and total noise) and 30 dB (railway) were censored to respective values. For nighttime noise a threshold of 25 dB was used for all transportation noise sources. This censoring was introduced to account for noises from various background sources that would be audible in the low exposure range (Héritier et al., 2017; Vienneau et al., 2019). PM_{10} exposures at home and school were extracted from a 200 m × 200 m grid (Meteotest, 2017) for each year. Weighted averages were calculated for each participant. While both NO_2 and PM_{10} were available, we chose PM_{10} as the marker for air pollution in our models, as it was less correlated with the noise exposure.

2.5. Statistical analysis

2.5.1. Main analyses

We conducted cross-sectional and longitudinal analyses to assess the linear association between road traffic noise exposure at home (L_{den}) and behaviour. For cross-sectional analyses, we jointly analysed data from the baseline and follow-up questionnaires by means of a random intercept mixed-effect model, with the individual as the cluster variable, to account for the fact that repeated observations within the same individual are correlated. For the longitudinal analysis, we subtracted the follow-up behavioural score from the baseline scores and related this value with noise exposure in a change score multivariate regression analysis. This allowed us to see the net effect of both, increase and decrease of behavioural problems in relation to noise exposure. We adjusted for sex, age, parents' education, participants' education, drinking, smoking, physical activity, screen time, nationality, PM_{10}, and bedroom orientation as well as difference in height (a proxy for puberty) for the longitudinal study. We created three models, (1) adjusting for sex and age, (2) adjusting for all other variables except bedroom orientation, (3) additionally adjusting for bedroom orientation.

2.5.2. Secondary analyses

We conducted several additional analyses to explore the associations of a variety of noise metrics with behavioural outcomes, at school and home, by adding them to the main cross-sectional model (Model 3) (L_{den} of the school, L_{day} at school, IR and N_{evt} at residence). We also examined alternative noise sources as the main exposure in model 3, by substituting following noise metrics with the main noise exposure: L_{den} by railway, L_{den} total (any road traffic, rail and aircraft noise) at home, and L_{night} at home.

In further analyses, we tested for interactions between modelled noise exposure and the following three variables: bedroom orientation, noise sensitivity, and road traffic noise annoyance.

2.5.3. Sensitivity analyses

To test the robustness of our findings, we conducted the following analyses.

We ran our main model with a modified noise exposure variable (called the "adjusted road traffic noise" (ARTN)), which accounted for information from the noise exposure calculations, bedroom orientation and whether or not the window was open during night. For this, we created a new main exposure variable by subtracting 10 dB if the participants' bedroom orientation was away from the loudest street by the house, and by subtracting a respective 10 dB or 28 dB for open or closed windows to estimate the indoor noise exposure (Locher et al., 2018).

In order to check for non-linear associations, we ran our main model with two binary versions of the categorized SDQ variable (normal versus borderline/severe and normal/borderline versus severe).

2.5.4. Missing data

We used multiple imputation (MI) to impute all missing data. MI is a method that allows for uncertainty in the imputed data by creating several plausible imputed data sets, analysing them and consolidating the results. We used the MICE (Multiple Imputation by Chained Equation) imputation algorithm from Stata to impute continuous and binary variables and created 20 imputed datasets. The following variables had N values missing which were therefore imputed: height (baseline (BL) = 15, follow-up (FU) = 52), weight (BL = 42, FU = 69), drinking (BL = 31, FU = 62), smoking (BL = 6, FU = 51), physical activity (BL = 3, FU = 47), screentime (BL = 245, FU = 138) and education level of parents (BL = 166). We also imputed SDQ variables, mostly due to non-participation at FU: emotional problems (46), conduct problems (46), hyperactivity/inattention (45), peer relationship problems (45), prosocial behaviour (45), as well as noise annoyance (BL = 4, FU = 48), noise sensitivity (BL = 44, FU = 81) and position of bedroom towards loudest street (BL = 7, FU = 47). We used the following complete variables to inform the imputation process: the five baseline SDQ outcome variables, school level of adolescent, nationality, urban/rural residence, PM_{10}, NDVI (as a measure of greenness), age at baseline. We used NDVI from Vienneau et al. (2017) in the imputation model and not in subsequent analyses. After imputation, the total difficulties score of the SDQ was calculated.

All analyses were done using Stata 15.1, several graphs were made using RStudio Version 4.1.1.

3. Results

3.1. Descriptives

In total, 44 schools with 899 students agreed to participate. In the first HERMES cohort, 19% of contacted schools and 37% of informed students participated. Participation rate was not tracked in the second HERMES cohort. Of the 899 participating adolescents, 13 were subsequently excluded from the analysis for the following reasons: four filled in the questionnaire but did not provide addresses, seven did not fill in the questionnaires, and two did not fill in the outcome variable in either the baseline or follow-up. Of the remaining 886 baseline participants, 854 (95%) took part in the follow-up, on average 376 days later.

In total, 387 of the included baseline participants were male (43.5%) (Table 1). Mean age at baseline was 14.0 (range: 10.4–17.0). Participants spread roughly evenly over the four school levels. About three fourth of the participants had two Swiss parents, while 14% had only one Swiss parent and 10% had two non-Swiss parents. None of the noise exposures varied noteworthy, while a slight trend can be seen in parents' nationality, being higher for participants who have one non-Swiss parent and even higher for participants with two non-Swiss parents. A little more than a third of participants had a bedroom facing the side of the loudest street; these experienced more road traffic noise on the most exposed façade (L_{den} = 56.5 dB) than adolescents sleeping away from

Table 1
A variety of noise exposure metrics by groups of covariates.

	N	mean L_{den} road home (dB)	mean L_{den} rail home (dB)	mean L_{night} home (dB (A))	mean L_{den} school (dB)	mean PM_{10} home (µg/m^3)
Overall mean of exposure		53.3	36.2	44.6	52.8	15.5
Sex						
Female	499	52.9	35.9	44.1	52.9	15.7
Male	387	54.0	36.6	45.2	52.8	15.4
Age						
<13	85	52.6	35.0	43.8	52.1	14.8
13 - <14	375	53.1	35.1	44.3	51.9	15.5
14 - <15	313	53.6	37.7	44.8	53.5	15.5
>15	113	54.2	36.6	45.4	54.7	16.2
bedroom orientation						
towards or side loudest street	319	56.5	36.5	47.7	53.0	15.6
away from loudest street	520	51.4	36.0	42.6	52.6	15.5
Drinking						
No	348	54.2	37.1	45.4	52.4	15.1
Yes	507	52.8	35.7	44.0	53.2	15.9
Smoking						
No	818	53.2	36.0	44.4	52.8	15.5
Yes	62	54.7	38.2	45.9	53.6	15.2
physical activity						
1–3x/month	95	53.5	35.3	44.8	53.0	15.2
1x/week	157	53.3	35.8	44.5	52.9	15.2
2–3 x week	318	53.0	35.4	44.2	52.7	15.6
4–6 x/week	166	53.1	35.9	44.3	52.3	15.5
every day	147	54.2	39.1	45.5	53.8	15.9
highest parents' education (lowest to highest)						
no education	7	54.9	34.9	46.2	54.3	16.5
mandatory school	24	59.0	42.4	50.2	53.6	16.2
training school "Berufslehre"	301	53.4	36.4	44.6	52.7	15.1
secondary school "Gymnasium"	60	51.0	37.0	42.3	52.2	15.6
college of higher education "Fachhochschule"	253	52.1	34.6	43.3	53.1	15.5
University	75	52.3	36.4	43.5	52.6	16.0
school level of participants (lowest to highest)						
Secondary school C	167	56.0	37.1	47.3	53.1	16.3
Secondary school B	249	54.0	37.0	45.2	54.0	15.3
Secondary school A	288	51.8	36.2	43.0	51.8	15.1
"Gymnasium"	182	52.5	34.5	43.7	52.7	15.9
nationality of parents						
both Swiss	673	52.6	35.4	43.8	52.7	15.3
Swiss and other	126	55.3	38.1	46.5	54.1	16.2
both other	87	56.6	39.8	47.9	52.1	16.1

Note: The data in the table reflects non-missings and therefore do not sum to 886 in all cases except for sex, age and nationality.

the street (L_{den} = 51.4 dB).

Table 2 shows the distribution of SDQ scales at baseline in the three categories of total difficulties (85% normal, 6% borderline and 9% abnormal) and corresponding mean transportation noise exposure. In relation to the subscales, hyperactivity/inattention had the highest proportion of abnormal (8%). For road traffic noise at home there was a tendency of higher noise levels for the abnormal group compared to the normal group, whereas for road traffic noise at school rather the opposite trends were observed. Mean outcome distributions from the continuous version of the data are shown in Supplement table S2.

Mean exposure for road traffic was 52.4 dB (interquartile range IQR: 10.1 dB) and 43.6 dB(A) L_{night} (IQR: 10.2 dB), (Fig. 1). Exposure to railway noise L_{den} was low, with 65.8% of the population assigned the censoring value of 30 dB. The distribution thus had a median of 30.0 and an IQR of 9.5 dB. The distribution of road traffic noise L_{den} at schools had a median at 53.2 dB, with a spike at 46.3 dB L_{den} reflecting exposure at the school with the largest study population. Aircraft noise data was censored at 30, which resulted in a mean L_{den} at 30.9 dB. More than 80% of data was less or equal to 30 dB, with only 1% of the rest of modelled exposures exceeding 40 dB. As these levels were very small, aircraft noise was not further considered.

Table 2
Noise metrics by groups of outcome variables of the Strengths and Difficulties Questionnaire at baseline.

		mean L_{den} road home (dB)	mean L_{den} rail home (dB)	mean L_{night} home (dB (A))	mean L_{den} school (dB)
Total difficulties score					
normal	753 (85%)	53.1	36.1	44.4	53.0
borderline	56 (6%)	55.6	37.5	46.9	52.4
abnormal	77 (9%)	53.7	35.7	44.9	52.1
Emotional difficulties					
normal	757 (85%)	53.3	36.3	44.6	52.9
borderline	59 (6%)	52.8	36.1	45.0	52.4
abnormal	70 (8%)	53.0	35.4	44.2	52.2
Conduct Problems					
Normal	774 (87%)	53.2	36.2	44.5	53.0
borderline	65 (7%)	53.0	35.1	44.2	52.2
abnormal	47 (5%)	55.4	35.8	46.7	51.6
Hyperactivity/inattention					
Normal	738 (83%)	53.4	36.2	44.6	52.9
Borderline	76 (9%)	53.4	36.5	44.6	52.0
Abnormal	72 (8%)	52.6	35.6	43.9	53.4
Peer relationship problems					
Normal	743 (84%)	53.0	36.0	44.2	52.9
Borderline	78 (9%)	54.4	37.8	45.6	53.4
Abnormal	65 (7%)	56.0	35.9	47.2	50.0
Prosocial behaviour					
Normal	722 (81%)	53.0	36.2	44.2	53.1
Borderline	85 (10%)	55.0	36.2	46.0	52.4
Abnormal	79 (9%)	55.1	35.9	46.4	51.0

Note: Due to rounding, not all percentages by behaviour category add up to 100%.
Ranges used for categorising the continuous outcome data are described in supplement table S1.

3.2. *Cross-sectional analyses of transportation noise with behavioural outcomes*

Model 1 shows the cross-sectional multilevel linear regression analysis adjusted for basic explanatory variables (Fig. 2 and supplement table S3). A significant association can be seen between modelled road traffic noise at home (L_{den}) and increased total difficulties, conduct problems, peer problems and prosocial skills. All associations, except for peer problems, disappeared when adjusting for all other covariates, except bedroom orientation (Model 2). After the additional adjustment for bedroom orientation (Model 3), the analysis did not change the general finding, yielding a significant association between modelled noise and increased peer problems. Peer relationship problem score increased by 0.15 (95%CI: 0.02, 0.27) units per 10 dB increase in noise at home. The total difficulties score was not significantly related to modelled L_{den} (0.16, 95% CI: −0.21, 0.53), but was 0.53 (95% CI: 0.09, 0.96) units higher for those adolescents whose bedroom faced the loudest street outside the house compared to those sleeping away from the street. Hyperactivity/inattention was increased by 0.25 (95% CI: 0.06, 0.44) units if the child's bedroom faced the loudest street (supplementary table S3).

3.3. *Longitudinal analyses of traffic noise with change in behavioural outcomes after one year*

In the longitudinal analyses, road traffic noise exposure (L_{den}) at home was mostly not associated with change in SDQ scales between baseline and follow up. In model 3, including orientation of the bedroom to the street and modelled noise exposure, the hyperactivity/inattention score decreased by 0.21 units (95%CI: −0.40, −0.03) per 10 dB increase (Fig. 3), while a higher hyperactivity/inattention score was found for adolescents whose bedroom faced the loudest street, compared to those whose bedroom faced the quiet street (0.35; 95%CI: 0.07, 0.63) (Supplementary table S4).

3.4. *Secondary analyses*

Additional noise exposure metrics (L_{den} road traffic noise at school, IR or the Number of events at home) added to the main model of the cross-sectional analysis were mostly not associated with behaviour outcomes. The exceptions were a significant negative association of road traffic noise L_{den} at school with peer problems and increased prosocial skills, which both were against our hypotheses. Further, substituting the modelled road traffic noise L_{den} at home (the main model) with alternative noise exposure metrics at home (L_{den} total, L_{night} road) did not change the associative trend of road traffic noise with outcome changes (Table 4). Railway noise was not related to any Strength and Difficulties scale.

3.5. *Sensitivity analyses*

ARTN did not show any significant association with the outcomes, although a tendency for an association can be seen for conduct problems (0.04 (95%CI: −0.02, 0.09)) and hyperactivity/inattention (0.05 (95% CI: −0.02, 0.12)) (Supplementary table S7).

The sensitivity analysis of the categorical SDQ outcomes showed a similar pattern but wider confidence intervals and no significance (Supplementary table S5). We found no interaction between bedroom facing the street, noise sensitivity or noise annoyance with road traffic noise L_{den} at home (Supplementary tables S6.1, 6.2 and 6.3 and figure S1).

Running the main analyses with a data set that excluded imputed outcome data resulted in no relevant changes of the results.

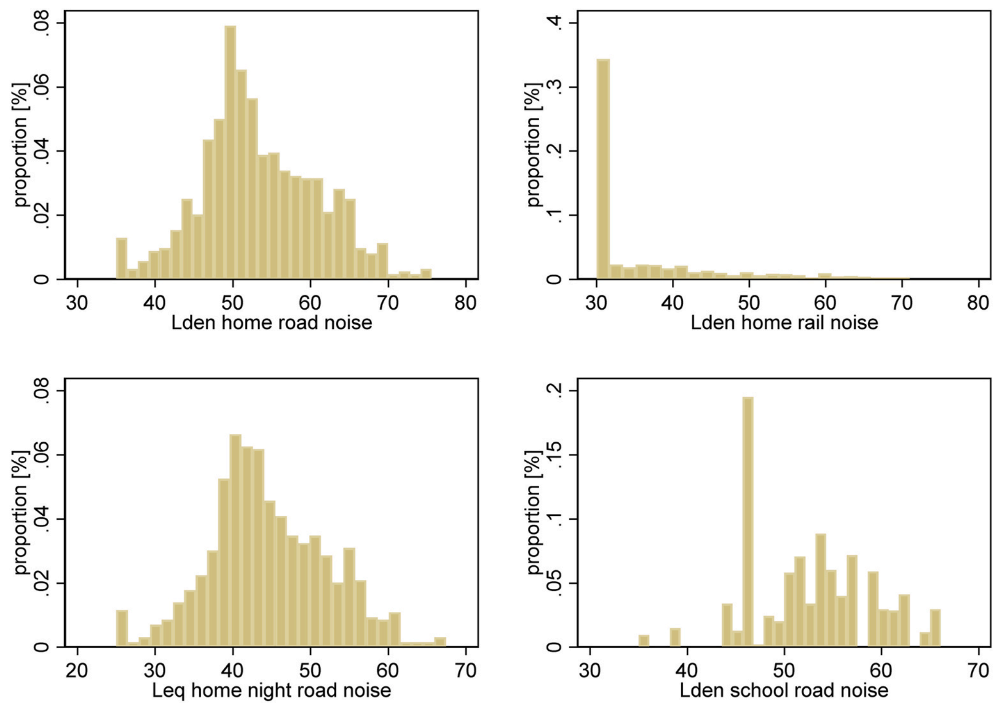

Fig. 1. Distribution of a selection of noise exposure metrics and sources.

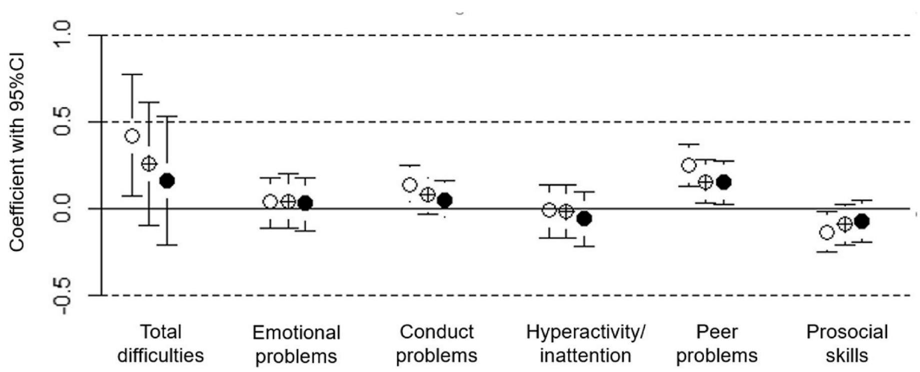

Fig. 2. Cross-sectional analyses: Multilevel analysis of modelled road noise at home (L_{den}) with SDQ outcomes. ○ Model 1 adjusted for sex and age. ⊕ Model 2 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}. ● Model 3 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards loudest street by house. Note: SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00–24:00), 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); complete tables for this data can be found in supplement table S3.

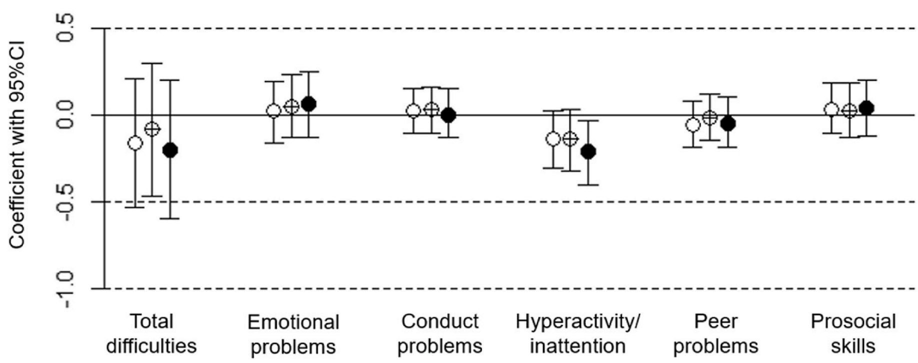

Fig. 3. Longitudinal analysis: Change score analysis of modelled noise at home (L_{den}) with change in SDQ outcomes after one year. ○ Model 1 adjusted for sex and age. ⊕ Model 2 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}, difference in height. ● Model 3 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}, difference in height, bedroom orientation towards loudest street by house. Note: SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00–24:00), 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); complete tables can be found in supplement table S4.

4. Discussion

More symptoms of peer problems were found in adolescents who experienced higher road traffic noise at home façades, although this could not confirmed in the longitudinal analyses with one year of follow-up. Within the same models, but acting independently of the modelled noise, adolescents that slept in rooms facing the street showed higher scores of hyperactivity/inattention. This association was confirmed in the longitudinal analysis looking at changes in hyperactivity/inattention between baseline and follow-up.

To put the outcomes of our analysis into perspective, we point out that the overall the associations we found were not very large. The

Table 3a
Secondary cross-sectional analysis: 2-pollutant multilevel analysis with L_{den} road at home and L_{den} road at school (day–evening–night noise level).

	L_{den} road traffic noise at home per 10 dB Coefficient (95%CI)	L_{den} road traffic noise at school per 10 dB Coefficient (95%CI)
Total difficulties	0.17 (−0.20, 0.54)	−0.28 (−0.70, 0.16)
Emotional problems	0.03 (−0.13, 0.19)	−0.03 (−0.22, 0.15)
Conduct problems	0.05 (−0.05, 0.16)	−0.06 (−0.18, 0.06)
Hyperactivity/ inattention	−0.06 (−0.22, 0.10)	0.01 (−0.17, 0.20)
Peer problems	**0.15 (0.03, 0.28)**	**−0.19 (-0.34, -0.04)**
Prosocial skills	−0.07 (−0.20.0.04)	**0.23 (0.09, 0.36)**

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00–24:00), 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); L_{day} (7:00–23:00).
Model 2 adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards loudest street by house.

Table 3b
Secondary cross-sectional analysis: 2-pollutant multilevel analysis with L_{den} road at home and L_{day} road at school (day noise level).

	L_{den} road traffic noise at home per 10 dB Coefficient (95%CI)	L_{day} road traffic noise at school per 10 dB Coefficient (95%CI)
Total difficulties	0.16 (−0.21, 0.53)	0.00 (−0.47, 0.47)
Emotional problems	0.03 (−0.13, 0.19)	0.01 (−0.19, 0.21)
Conduct problems	0.06 (−0.05, 0.16)	−0.07 (−0.20, 0.07)
Hyperactivity/ inattention	−0.06 (−0.23, 0.10)	0.03 (−0.18, 0.23)
Peer problems	**0.14 (0.02, 0.27)**	0.03 (−0.13, 0.19)
Prosocial skills	−0.08 (−0.20, 0.04)	0.11 (−0.04, 0.26)

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00–24:00), 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); L_{day} (7:00–23:00).
*Model 2 adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards loudest street by house.

Table 3c
Secondary cross-sectional analysis: 2-pollutant multilevel analysis with L_{den} road at home and Intermittency Ratio for road at home (IR).

	L_{den} road traffic noise at home per 10 dB Coefficient (95%CI)	IR of road traffic noise at home Coefficient (95% CI)**">**
Total difficulties	0.16 (−0.21, 0.53)	−0.20 (−10.16, 9.75)
Emotional problems	0.03 (−0.13, 0.19)	0.38 (−3.86, 4.62)
Conduct problems	0.05 (−0.05, 0.16)	−0.28 (−3.14, 2.59)
Hyperactivity/ inattention	−0.06 (−0.22, 0.10)	−0.56 (−4.91, 3.79
Peer problems	**0.14 (0.02, 0.27)**	0.20 (−3.26, 3.65)
Prosocial skills	−0.07 (−0.05, 0.19)	0.62 (−3.89, 2.66)

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00–24:00), 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); L_{day} (7:00–23:00); IR: Intermittency Ratio.
Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards loudest street by house.
**Coefficient multiplied by 1000.

Table 3d
Secondary cross-sectional analysis: 2-pollutant multilevel analysis with L_{den} road at home and Number of events (N_{evt}).

	L_{den} road traffic noise at home per 10 dB Coefficient (95%CI)	Number of events of road traffic noise at home Coefficient (95% CI)**">**
Total difficulties	0.05 (−0.43, 0.54)	0.17 (−0.32, 0.67)
Emotional problems	−0.03 (−0.24, 0.17)	0.10 (−0.11, 0.31)
Conduct problems	0.10 (−0.03, 0.24)	−0.09 (−0.23, 0.06)
Hyperactivity/ inattention	−0.11 (−0.32, 0.10)	0.08 (−0.14, 0.30)
Peer problems	0.10 (−0.07, 0.26)	0.08 (-0.10, 0.25)
Prosocial skills	−0.16 (−0.32, 0.00)	0.14 (−0.02, 0.30)

Note: Significant results at the 95% CI level are highlighted in bold. SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00–24:00), 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); L_{day} (7:00–23:00); IR: Intermittency Ratio.
Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards loudest street by house.
**Coefficient multiplied by 1000.

Table 4
Secondary cross-sectional analyses: multilevel analysis replacing the L_{den} road noise metric with different noise exposures at home.

	L_{den} road (model 3)	L_{den} total[a]	L_{night} road	L_{den} railway
	Increase L_{den} by 10 dB	Increase L_{den} by 10 dB	Increase L_{night} by 10 dB(A)	Increase L_{den} by 10 dB
Total difficulties	0.16 (−0.21, 0.53)	0.14 (−0.21, 0.49)	0.16 (−0.21, 0.52)	0.01 (−0.26, 0.27)
Emotional problems	0.03 (−0.13, 0.18)	0.03 (−0.12, 0.18)	0.03 (−0.13, 0.18)	0.03 (−0.09, 0.14)
Conduct problems	0.05 (−0.05, 0.16)	0.03 (−0.07, 0.13)	0.05 (−0.05, 0.15)	0.01 (−0.07, 0.08)
Hyperactivity/ inattention	−0.06 (−0.22, 0.10)	−0.04 (−0.19, 0.11)	−0.06 (−0.22, 0.10)	0.02 (−0.10, 0.14)
Peer problems	**0.15 (0.02, 0.27)**	**0.12 (0.00, 0.24)**	**0.14 (0.02, 0.27)**	−0.05 (−0.14, 0.05)
Prosocial skills	−0.07 (−0.19, 0.05)	−0.06 (−0.18, 0.06)	−0.05 (−0.19, 0.05)	0.02 (−0.07, 0.11)

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00–24:00), 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00); L_{night} (23:00–07:00).
Models adjusted for sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards loudest street by house.
[a] L_{den} total: combined L_{den} of road traffic, railway and aircraft noise.

difference in ratings on the 'peer problem' scale (ranging from 0 to 10) between adolescents who were exposed to more noise than other adolescents was higher by only 0.15 (95%CI: 0.02, 0.27) units per additional 10 dB L_{den}. Within our study all significant and non-significant effect sizes are not exceeding the 0.5 units change mark, and are similar to another study of comparable methodology (Stansfeld et al., 2009). Peer problems have been explored in all studies on the association between SDQ and noise exposure of various noise sources (Haines et al., 2001; Stansfeld et al., 2009; Tiesler et al., 2013). To the best of our knowledge, however, it has only once been shown to be associated with any noise source, specifically with railway noise (Hjortebjerg et al., 2016). We therefore assume this a chance finding. Adding the school L_{den} variable into the model did not change in our main finding, but we did see that noise exposure at school was itself inversely associated with 'peer problems'. Although a similar inverse association on another behavioural outcome (ADHD diagnosis) was found for noise in schools (Zijlema et al., 2021), we consider bias, exposure misclassification or chance a more likely explanation for this finding. Exposure assessment for school buildings is more complex than for homes because schools often consist of several larger buildings where children and adolescents move from one classroom to the other. This is especially the case for adolescents, who have more complex school curriculums. In our case, we did not know in which building or classroom the students spent most of their time and only had one representative noise variable geocoded per school. Moreover, the higher the traffic noise is in front of schools, the more likely it is that windows on those façades got double or triple glazing to reduce indoor noise. In addition, we can assume the overall noise within classrooms to be rather loud due to other noise sources, such as the pupils themselves. A survey in England found average lesson noise in high schools to be 64 dB(A) (Shield et al., 2015), which means that moderate levels of road traffic noise may be of minor relevance compared to the existing inside noise level. All these factors may increase exposure misclassification, possibly even in systematic noise-dependent ways.

We expected to find bedroom orientation modulating the relationship of maximum façade noise estimates per dwelling and outcome. Indeed, there are some indications for this. When adding bedroom orientation into the models some of that association has transferred to the bedroom orientation variable. As a consequence, the bedroom orientation variable showed its own independent associations with some behavioural outcomes: total difficulties, conduct problems and hyperactivity/inattention in the cross-sectional analysis, and hyperactivity/inattention in the longitudinal analysis. In addition, adding bedroom orientation resulted in a decrease of the coefficients for the associations between modelled L_{den} and these outcomes. In the case of hyperactivity/inattention, the modelled noise variable became even significantly inversely associated with hyperactivity/inattention, which, however, is difficult to interpret.

Notably, we found no significant interaction of bedroom orientation with modelled noise in the range of noise we investigated (Supplementary table S6 and graph S1). This finding stands in contrast to a study which found a significant moderating effect of bedroom orientation on the relationship of noise exposure and health outcome (Brink et al., 2019). We also expected the sensitivity analysis with the noise variable ARTN to show a stronger association with the outcome variables as in previous findings using a similar method (Foraster et al., 2014). However, in our cohort mean road traffic L_{den} was 52.4 dB (IQR: 10.1 dB). This means that reducing modelled road traffic noise exposure for adolescents sleeping away from the loudest street or with closed windows by 20–38 dB decreased noise exposure close to our censoring level of 25–35 dB (depending on noise source and time of day). This is turn would mean that any adolescents sleeping to the back of the house experience the same –very low – noise exposure around censoring levels, no matter how loud the modelled street façade noise is, which may explain why we observed mostly absence of associations.

The association between hyperactivity/inattention and bedroom orientation coefficient in Model 3 of the cross-sectional and longitudinal analyses (Fig. 2+3 and supplementary tables 3+4), might imply orientation of the bedroom to a noisy street is a more relevant proxy than maximum façade noise per dwelling. A possible explanation is that road traffic noise during sleep might affect hyperactivity. This underpins the most common finding of previous studies that show an association between modelled road traffic noise and hyperactivity/inattention (Schubert et al., 2019).

One could argue that if the observed association of bedroom orientation with behavioural outcomes is created by noise, it must be aspects of noise that are not captured in the variable L_{den}. One of these would be bursts of few sudden noises (for example motorized vehicles accelerating), but we could not improve our model when adding IR or N_{evt}. Some noise qualities are even less easily modelled, such as neighbour noise, and were not considered.

The relationship of bedroom orientation with outcome variables could also be interpreted as the bedroom variable being an indirect indicator of residual confounding such as higher air pollution levels or social disadvantage. Poorer households might have more bedrooms facing noisy roads, because apartments in noise-exposed areas are cheaper. In addition, cheaper apartments may have fewer rooms facing the more quiet back of the building, and the number of inhabitants per apartment may be higher for social disadvantaged families. Thus, these children may be more likely to use a sleeping room facing a noisy street and to share their room with other children. This interpretation assumes that lower socioeconomic status is not completely adjusted for with parental education.

Despite the high-quality noise exposure modelling, we face several sources of exposure misclassification for school modelling as explained above. Further, there was practical problem of the questionnaire item on bedroom orientation: In the first study phase, a binary question was used to evaluate whether or not participants slept towards the loudest street that passed their house. It became clear that more options, such as 'sleeping to the side of the loudest street' or 'there are no loud streets near our house' (Brink et al., 2019) should be integrated in future attempts. This problem is expected to contribute to non-differential exposure misclassification, rather underestimating a true risk than creating a spurious association. Another limitation is non-participation at baseline. Cross-sectional analyses may thus be subject to selection bias if likelihood to participate was related to noise exposure and behaviour. In contrast, participation at follow-up was very high (95%), and thus the corresponding analysis is very unlikely to be affected by selection bias.

The main strength of this study was the longitudinal analysis of behaviour changes within one year with detailed noise exposure data such as L_{den}, L_{night}, IR or N_{evt}, as well as information about noise relevant behaviour (window open/closed at night and bedroom orientation) and other relevant confounder information. We have used a comprehensive noise exposure modelling, for both home and school, which allowed us to explore associations with different noise metrics and noise sources in great detail.

In general, associations in the longitudinal analyses were less pronounced than in the cross-sectional analysis. Longitudinal analyses are usually considered superior to cross-sectional analyses due to less confounding. However, a follow-up of one year may be too short to capture any change. Other speculations are around the question of how noise influences behaviour over time. In particular, does noise continuously worsen the examined behaviours, or does the effect plateau, after a certain time. In the latter case, any child that lived with noise and had not moved recently might have not changed their outcome due to noise, because they had reached their maximum behavioural deterioration point. There might also be a difference in how and when children and adolescents are most susceptible to noise as a Brazilian study found cross-sectional and longitudinal associations in preschool children (Raess et al., 2022). Thus, in these specific situations, results from cross-sectional studies may also be important, similar to noise studies on other chronic diseases like blood pressure (Bilenko et al., 2015). Another point is that the associations found by both analyses might be more prominent if the sample size of the population was bigger and noise exposure higher and with more contrast between participants.

5. Conclusions

We found some indications that road traffic noise is associated with problem behaviour in adolescents, although associations were small compared to other factors. Future studies should also carefully consider the orientation of the bedroom in relation to the noise sources and other relevant factors.

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Ethics

The HERMES study was approved by the Ethics Committees of the Northwest – and Central Switzerland on 08.06.2018 (Project-ID, 2018–00980).

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.

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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.2021.112645.

References

Babisch, W., Ising, H., Gallacher, J.E., Sweetnam, P.M., Elwood, P.C., 1999. Traffic noise and cardiovascular risk: the Caerphilly and Speedwell studies, third phase-10-year follow up. Arch. Environ. Health 54 (3), 210–216.

BAFU, 2009. SonBase - die GIS-Lärmdatenbank der Schweiz (Grundlagen. Retrieved from Bern).

Becker, A., Wang, B., Kunze, B., Otto, C., Schlack, R., Hölling, H., Isensee, C., 2018. Normative data of the self-report version of the German Strengths and Difficulties Questionnaire in an epidemiological setting. In: Zeitschrift für Kinder-und Jugendpsychiatrie und Psychotherapie.

Belojevic, G., Evans, G.W., Paunovic, K., Jakovljevic, B., 2012. Traffic noise and executive functioning in urban primary school children: the moderating role of gender. J. Environ. Psychol. 32 (4), 337–341.

Bilenko, N., Rossem, L.v., Brunekreef, B., Beelen, R., Eeftens, M., Hoek, G., Koppelman, G.H., 2015. Traffic-related air pollution and noise and children's blood pressure: results from the PIAMA birth cohort study. Euro. J. Prevent. Cardiol. 22 (1), 4–12.

Brink, M., Schäffer, B., Vienneau, D., Pieren, R., Foraster, M., Eze, I.C., Probst-Hensch, N., 2019. Self-reported sleep disturbance from road, rail and aircraft noise: exposure-response relationships and effect modifiers in the SiRENE study. Int. J. Environ. Res. Publ. Health 16 (21), 4186.

Clark, C., Crombie, R., Head, J., Van Kamp, I., Van Kempen, E., Stansfeld, S.A., 2012. Does traffic-related air pollution explain associations of aircraft and road traffic noise exposure on children's health and cognition? A secondary analysis of the United Kingdom sample from the RANCH project. Am. J. Epidemiol. 176 (4), 327–337.

Clark, C., Head, J., Stansfeld, S.A., 2013. Longitudinal effects of aircraft noise exposure on children's health and cognition: a six-year follow-up of the UK RANCH cohort. J. Environ. Psychol. 35, 1–9.

Dreger, S., Meyer, N., Fromme, H., Bolte, G., 2015. Environmental noise and incident mental health problems: a prospective cohort study among school children in Germany. Environ. Res. 143, 49–54.

Empa, 2010. FLULA2, Ein Verfahren zur Berechnung und Darstellung der Fluglärmbelastung (Retrieved from Dübendorf:).

Foerster, M., Thielens, A., Joseph, W., Eeftens, M., Röösli, M., 2018. A prospective cohort study of adolescents' memory performance and individual brain dose of microwave radiation from wireless communication. Environ. Health Perspect. 126 (7), 077007.

Foraster, M., Künzli, N., Aguilera, I., Rivera, M., Agis, D., Vila, J., Ramos, R., 2014. High blood pressure and long-term exposure to indoor noise and air pollution from road traffic. Environ. Health Perspect. 122 (11), 1193.

Goodman, R., 1997. The strengths and difficulties questionnaire: a research note. JCPP (J. Child Psychol. Psychiatry) 38 (5), 581–586.

Haines, M.M., Stansfeld, S.A., Brentnall, S., Head, J., Berry, B., Jiggins, M., Hygge, S., 2001. The West London Schools Study: the effects of chronic aircraft noise exposure on child health. Psychol. Med. 31 (8), 1385.

Héritier, H., Vienneau, D., Foraster, M., Eze, I.C., Schaffner, E., Thiesse, L., Pieren, R., 2017. Transportation noise exposure and cardiovascular mortality: a nationwide cohort study from Switzerland. Eur. J. Epidemiol. 32 (4), 307–315.

Hjortebjerg, D., Andersen, A.M.N., Christensen, J.S., Ketzel, M., Raaschou-Nielsen, O., Sunyer, J., Sørensen, M., 2016. Exposure to road traffic noise and behavioral problems in 7-year-old children: a cohort study. Environ. Health Perspect. 124 (2), 228.

Karipidis, I., Vienneau, D., Habermacher, M., Köpflii, M., Brink, M., Probst-Hensch, N., Wunderli, J.-M., 2014. Reconstruction of historical noise exposure data for environmental epidemiology in Switzerland within the SiRENE project. Noise Mapp. 1 (1) https://doi.org/10.2478/noise-2014-0002.

Locher, B., Piquerez, A., Habermacher, M., Ragettli, M., Röösli, M., Brink, M., Müller, U., 2018. Differences between outdoor and indoor sound levels for open, tilted, and closed windows. Int. J. Environ. Res. Publ. Health 15 (1), 149.

Meteotest, 2017. Karten von Jahreswerten der Luftbelastung in der Schweiz. Datengrundlagen, Berechnungsverfahren und Resultaten der Karten bis zum Jahr 2016 (Retrieved from Bern).

Peris, E., 2020. Environmental noise in Europe: 2020. Eur. Environ. Agency 1, 104.

Pietrzko, S., Hofmann, R., 1988. Prediction of A-weighted aircraft noise based on measured directivity patterns. Appl. Acoust. 23 (1), 29–44.

Raess, M., Brentani, A.V.M., Flückiger, B., de Campos, B.L.d.A., Fink, G., Röösli, M., 2022. Association between community noise and children's cognitive and behavioral development: a prospective cohort study. Environ. Int. 158, 106961.

Roser, K., Schoeni, A., Foerster, M., Röösli, M., 2016. Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour? Int. J. Publ. Health 61 (3), 307–315.

Schubert, M., Hegewald, J., Freiberg, A., Starke, K. R., Augustin, F., Riedel-Heller, S. G., . . . health, p. (2019). Behavioral and emotional disorders and transportation noise among children and adolescents: a systematic review and meta-analysis. 16(18), 3336.

Shield, B., Conetta, R., Dockrell, J., Connolly, D., Cox, T., Mydlarz, C., 2015. A survey of acoustic conditions and noise levels in secondary school classrooms in England. J. Acoust. Soc. Am. 137 (1), 177–188.

Stansfeld, S.A., Clark, C., Cameron, R.M., Alfred, T., Head, J., Haines, M.M., López-Barrio, I., 2009. Aircraft and road traffic noise exposure and children's mental health. J. Environ. Psychol. 29 (2), 203–207.

Tiesler, C.M., Birk, M., Thiering, E., Kohlböck, G., Koletzko, S., Bauer, C.-P., Heinrich, J., 2013. Exposure to road traffic noise and children's behavioural problems and sleep disturbance: results from the GINIplus and LISAplus studies. Environ. Res. 123, 1–8.

Vienneau, D., de Hoogh, K., Faeh, D., Kaufmann, M., Wunderli, J.M., Röösli, M., Group, S.S., 2017. More than clean air and tranquillity: residential green is independently associated with decreasing mortality. Environ. Int. 108, 176–184.

Vienneau, D., Héritier, H., Foraster, M., Eze, I.C., Schaffner, E., Thiesse, L., Pieren, R., 2019. Façades, floors and maps–Influence of exposure measurement error on the association between transportation noise and myocardial infarction. Environ. Int. 123, 399–406.

Weyde, K.V., Krog, N.H., Oftedal, B., Magnus, P., Øverland, S., Stansfeld, S., Aasvang, G. M., 2017. Road traffic noise and children's inattention. Environ. Health 16 (1), 127.

Weyde, K.V., Krog, N.H., Oftedal, B., Magnus, P., White, R., Stansfeld, S., Aasvang, G.M., 2018. A longitudinal study of road traffic noise and body mass index trajectories from birth to 8 years. Epidemiology.

WHO, 2009. Night noise guidelines for Europe (9289041730). Retrieved from. http://www.euro.who.int/_data/assets/pdf_file/0017/43316/E92845.pdf.

Wunderli, J.M., Pieren, R., Habermacher, M., Vienneau, D., Cajochen, C., Probst-Hensch, N., Brink, M., 2016. Intermittency ratio: a metric reflecting short-term temporal variations of transportation noise exposure. J. Expo. Sci. Environ. Epidemiol. 26 (6), 575–585.

Zijlema, W.L., De Kluizenaar, Y., Van Kamp, I., Hartman, C.A., 2021. Associations between road traffic noise exposure at home and school and ADHD in school-aged children: the TRAILS study. Eur. Child Adolesc. Psychiatr. 30 (1), 155–167.

Zimmer, K., Ellermeier, W., 1998. Ein Kurzfragebogen zur Erfassung der Lärmempfindlichkeit. Umweltpsychologie 2, 54–63.

Supplements:

Table S1. Cut-off points for psychological attributes of a representative German sample of adolescents

Table S2. Mean levels of continuous SDQ score at baseline and follow-up

Table S3. Cross-sectional analyses: Multilevel analysis of modelled road noise at home (Lden) with SDQ outcomes

Table S4. Longitudinal analysis: Change score analysis of modelled noise at home (Lden) with change in SDQ outcomes after one year

Table S5. Cross-sectional analyses: Multilevel analysis of categorical SDQ variable in relation to road traffic noise L_{den} at home

Table S6. Cross-sectional analyses: Multilevel analysis of the association between road traffic noise in L_{den} at home and behavioural outcomes with an interaction between road traffic noise in L_{den} exposure at home and bedroom orientation, sensitivity or annoyance.

Figure S1. Cross-sectional analyses: Multilevel analysis of the association between road traffic noise in L_{den} at home and behavioural outcomes with an interaction between road traffic noise in L_{den} exposure at home and bedroom orientation

Table S7. Cross-sectional analyses: Multilevel analysis with ARTN (not adjusted for bedroom orientation)

Table S2. Cut-off points for psychological attributes of a representative German sample of adolescents

	Normal	Borderline	Abnormal
Total difficulties score*	0-14	15-16	17-40
Emotional difficulties	0-4	5	6-10
Conduct problems	0-3	4	5-10
Hyperactivity/inattention	0-5	6	7-10
Peer problems	0-3	4	5-10
Prosocial behaviour*	7-10	6	0-5

Note: * total behaviour score is a sum of emotional difficulties, conduct problems, hyperactivity/inattention and peer problems
** prosocial behaviour is a positive trait and therefore coded in reverse.

Table S2. Mean levels of continuous SDQ score at baseline and follow-up

	Range	Mean at baseline (N)	Mean at follow-up (N)
Total difficulties score	0-40	9.9 (886)	9.1(840)
Emotional difficulties	0-10	2.4 (886)	2.4 (840)
Conduct Problems	0-10	1.8 (886)	1.4 (840)
Hyperactivity/inattention	0-10	3.6 (886)	3.2 (841)
Peer relationship problems	0-10	2.1 (886)	2.0 (840)
Prosocial behaviour	0-10	8.0 (886)	8.2 (840)

Note: *total behaviour score is a sum of emotional difficulties, conduct problems, hyperactivity/inattention and peer problems
**prosocial behaviour is a positive trait and therefore coded in reverse.

Table S3. Cross-sectional analyses: Multilevel analysis of modelled road noise at home (Lden) with SDQ outcomes

	Model 1*	Model 2**	Model 3***
		Coefficient (95% CI)	
Total difficulties			
Road noise (10 dB)	**0.42 (0.07, 0.77)**	0.26 (-0.10, 0.61)	0.16 (-0.21, 0.53)
Sleeping towards street	**-**	**-**	**0.53 (0.09, 0.96)**
Emotional problems			
Road noise (10 dB)	0.04 (-0.11, 0.18)	0.04 (-0.11, 0.20)	0.03 (-0.13, 0.18)
Bedroom towards street	**-**	-	0.08 (-0.12, 0.28)
Conduct problems			
Road noise (10 dB)	**0.14 (0.04, 0.25)**	0.08 (-0.03, 0.18)	0.05 (-0.05, 0.16)
Bedroom towards street	**-**	**-**	**0.14 (0.00, 0.28)**
Hyperactivity/ inattention			
Road noise (10 dB)	-0.01 (-0.17, 0.14)	- 0.02 (-0.17, 0.14)	- 0.06 (-0.22, 0.10)
Bedroom towards street	**-**	**-**	**0.25 (0.06, 0.44)**
Peer problems			
Road noise (10 dB)	**0.25 (0.13, 0.37)**	**0.15 (0.03, 0.28)**	**0.15 (0.02, 0.27)**
Bedroom towards street	**-**	-	0.05 (-0.11, 0.21)
Prosocial skills			
Road noise (10 dB)	**-0.14 (-0.02, -0.25)**	-0.09 (-0.21, 0.02)	- 0.07 (-0.19, 0.05)
Bedroom towards street	**-**	-	- 0.13 (-0.29,0.02)

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00-24:00), 5 dB penalty for the evening noise (18:00-23:00) and 10 dB penalty for the night noise (23:00-07:00)

* Model 1 adjusted for sex and age

** Model 2 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}

*** Model 3 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards loudest street by house

Table S4. Longitudinal analysis: Change score analysis of modelled noise at home (Lden) with change in SDQ outcomes after one year

	Model 1*	Model 2**	Model 3***
		Coefficient (95% CI)	
Total difficulties			
Road noise (10 dB)	-0.16 (-0.53, 0.21)	-0.08 (-0.47, 0.30)	-0.20 (-0.60, 0.20)
Sleeping towards street	-	-	0.55 (-0.06, 1.17)
Emotional problems			
Road noise (10 dB)	0.02 (-0.16, 0.19)	0.05 (-0.13, 0.23)	0.06 (-0.13, 0.25)
Bedroom towards street	-	-	-0.06 (-0.36, 0.24)
Conduct problems			
Road noise (10 dB)	0.02 (-0.11, 0.15)	0.03 (-0.11, 0.16)	0.00 (-0.13, 0.15)
Bedroom towards street	-	-	0.09 (-0.13, 0.31)
Hyperactivity/ inattention			
Road noise (10 dB)	-0.14 (-0.31, 0.02)	-0.14 (-0.32, 0.03)	**-0.21 (-0.40, -0.03)**
Bedroom towards street	-	-	**0.35 (0.07, 0.63)**
Peer problems			
Road noise (10 dB)	-0.06 (-0.19, 0.08)	-0.02 (-0.15, 0.12)	-0.05 (-0.19, 0.10)
Bedroom towards street	-	-	0.16 (-0.07, 0.38)
Prosocial skills			
Road noise (10 dB)	0.03 (-0.11, 0.18)	0.02 (-0.13, 0.18)	0.04 (-0.12, 0.20)
Bedroom towards street	-	-	-0.09 (-0.33, 0.16)

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00-24:00), 5 dB penalty for the evening noise (18:00-23:00) and 10 dB penalty for the night noise (23:00-07:00);

* Model 1 adjusted for sex and age

** Model 2 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}, difference in height

*** Model 3 adjusted for sex, age, drinking any alcohol, smoking, screentime, parents' education, nationality, school level, physical activity, PM_{10}, difference in height, bedroom orientation towards loudest street by house

Table S5. Cross-sectional analyses: Multilevel analysis of categorical SDQ variable in relation to road traffic noise L_{den} at home

	Cross-sectional		longitudinal	
	Model 1*	Model 3**	Model 1*	Model 3**
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Total difficulties				
Road noise (1 dB)	1.03 (0.99, 1.07)	0.98 (0.93, 1.02)	1.04 (0.99, 1.09)	1.01 (0.96, 1.06)
Sleeping towards street	-	1.69 (0.93, 3.08)	-	1.78 (0.90, 3.55)
Emotional problems				
Road noise (1 dB)	1.01 (0.96, 1.05)	1.03 (0.98, 1.08)	1.01 (0.95, 1.05)	1.01 (0.96, 1.07)
Bedroom towards street	-	1.07 (0.57, 2.00)	-	1.10 (0.52, 2.32)
Conduct problems				
Road noise (1 dB)	**1.06 (1.01, 1.11)**	1.03 (0.98, 1.08)	1.03 (0.96, 1.11)	1.00 (0.91, 1.09)
Bedroom towards street	-	1.23 (0.60, 2.49)	-	1.63 (0.49, 5.41)
Hyperactivity/ inattention				
Road noise (1 dB)	0.97 (0.93, 1.02)	0.97 (0.93, 1.01)	0.98 (0.94, 1.04)	0.98 (0.93, 1.04)
Bedroom towards street	-	1.31 (0.71, 2.43)	-	1.02 (0.45, 2.29)
Peer problems				
Road noise (1 dB)	**1.06 (1.01, 1.11)**	1.03 (0.98, 1.08)	1.04 (0.98, 1.09)	1.03 (0.98, 1.09)
Bedroom towards street	-	1.31 (0.70, 2.47)	-	0.64 (0.27, 1.50)
Prosocial skills				
Road noise (1dB)	**0.97 (0.93, 1.00)**	0.93 (0.81, 1.06)	0.95 (0.85, 1.06)	0.93 (0.82, 1.07)
Bedroom towards street	-	3.30 (0.55, 19.66)	-	3.14 (0.54, 1.36)

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; OR, Odds ratio; L_{den} (00:00-24:00), 5 dB penalty for the evening noise (18:00-23:00) and 10 dB penalty for the night noise (23:00-07:00)

* Model 1 adjusted for sex and age

** Model 3 adjusted for sex, age, drinking any alcohol, smoking, screen time, parents education, nationality, school level, physical activity, PM_{10}, bedroom orientation towards street

Table S6.1. Cross-sectional analyses: multilevel analysis of the association between road traffic noise in L_{den} at home and behavioural outcomes with an interaction between road traffic noise in L_{den} exposure at home and bedroom orientation towards loudest street

	Road noise (10 dB) coefficient (95% CI)	Interaction road noise * bedroom orientation coefficient (95% CI)	bedroom orientation towards loudest street coefficient (95% CI)
Total difficulties	0.19 (-0.24, 0.61)	-0.07 (-0.64, 0.51)	0.89 (-2.28, 4.07)
Emotional problems	0.08 (-0.11, 0.26)	-0.12 (-0.49, 0.14)	0.76 (-0.69, 2.20)
Conduct problems	0.06 (-0.07, 0.19)	-0.02 (-0.21, 0.17)	0.25 (-0.77, 1.28)
Hyperactivity/inattention	-0.08 (-0.27, 0.11)	0.05 (-0.21, 0.31)	-0.01 (-1.44, 1.41)
Peer problems	**0.15 (0.00, 0.30)**	-0.01 (-0.22, 0.20)	0.10 (-1.07, 1.27)
Prosocial skills	-0.09 (-0.24, 0.05)	0.07 (0.14, 0.28)	-0.53 (-1.69, 0.64)

Note: Significant results at significance level of 5% level are highlighted in bold.

Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, participants' school level, physical activity, PM_{10}, bedroom orientation towards street

S6.2. Cross-sectional analyses: multilevel analysis of the association between road traffic noise in L_{den} at home and behavioural outcomes with an interaction between road traffic noise in L_{den} exposure at home and noise sensitivity

	Road noise (10 dB) coefficient (95% CI)	Interaction road noise * bedroom orientation coefficient (95% CI)	bedroom orientation towards loudest street coefficient (95% CI)
Total difficulties	0.17 (-0.90, 1.24)	0.00 (-0.09, 0.09)	0.19 (-0.28, 0.66)
Emotional problems	0.03 (-0.45, 0.51)	0.00 (-0.04, 0.04)	0.07 (-0.14, 0.05)
Conduct problems	0.09 (-0.26, 0.45)	0.00 (-0.03, 0.03)	-0.05 (-0.11, 0.20)
Hyperactivity/inattention	-0.09 (-0.57, 0.40)	0.00 (-0.04, 0.04)	0.02 (-0.20, 0.24)
Peer problems	0.12 (-0.26, 0.51)	0.00 (-0.03, 0.03)	0.06 (-0.11, 0.23)
Prosocial skills	0.12 (-0.29, 0.53)	-0.02 (-0.05, 0.02)	0.06 (-0.12, 0.24)

Note: Significant results at significance level of 5% level are highlighted in bold.

Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, participants' school level, physical activity, PM_{10}, bedroom orientation towards street

Table S6.3. Cross-sectional analyses: multilevel analysis of the association between road traffic noise in L_{den} at home and behavioural outcomes with an interaction between road traffic noise in L_{den} exposure at home and road traffic noise annoyance

	Road noise (10 dB) coefficient (95% CI)	Interaction road noise * road traffic noise annoyance coefficient (95% CI)	road traffic noise annoyance coefficient (95% CI)
Total difficulties	-0.12 (-0.25, 0.49)	0.71 (-0.62, 2.03)	-3.42 (-11.04, 4.20)
Emotional problems	0.01 (-0.15, 0.17)	0.47 (-0.12, 1.06)	-2.73 (-6.11, 0.66)
Conduct problems	0.03 (-0.08, 0.14)	0.35 (-0.08, 0.78)	-1.73 (-4.19, 0.74)
Hyperactivity/inattention	-0.06 (-0.23, 0.10)	-0.11 (-0.70, 0.49)	0.88 (-2.53, 4.28)
Peer problems	**0.13 (0.01, 0.26)**	0.09 (-0.40, 0.58)	-0.16 (-2.99, 2.58)
Prosocial skills	-0.06 (-0.18, 0.07)	-0.16 (-0.67, 0.35)	0.66 (-2.26, 3.59)

Note: Significant results at significance level of 5% level are highlighted in bold.

Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, participants' school level, physical activity, PM_{10}, bedroom orientation towards street

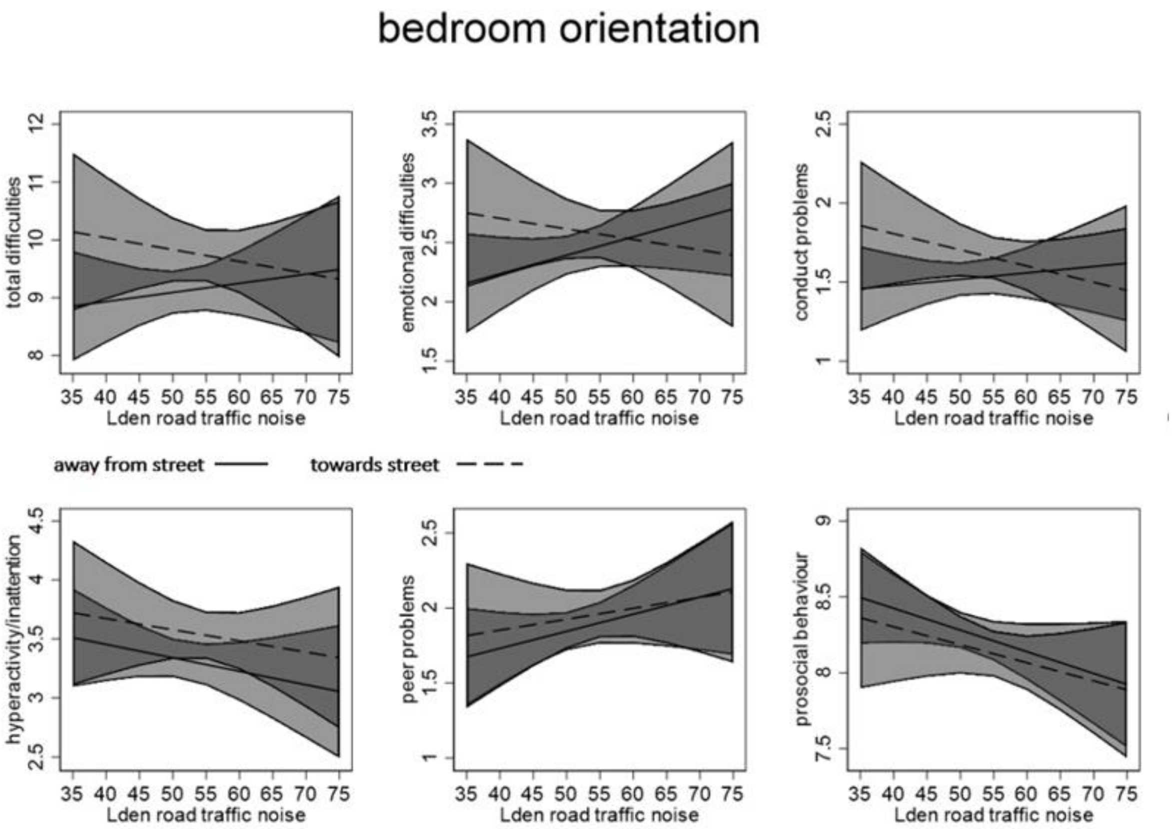

Figure S1. Cross-sectional analyses: multilevel analysis of the association between road traffic noise in L_{den} at home and behavioural outcomes with an interaction between road traffic noise in L_{den} exposure at home and bedroom orientation

Note: Due to limitations of the MI program, this analysis is based on a complete case scenario and therefore slightly different to the analysis depicted in table S6 column 2.

Table S7. Cross-sectional analyses: Multilevel analysis with ARTN (not adjusted for bedroom orientation)

	Cross-sectional multilevel analysis*	Longitudinal change score analysis**
	Increase L_{den} by 10 dB	Increase L_{den} by 10 dB
Total difficulties	0.09 (-0.07, 0.26)	0.09 (-0.07, 0.26)
Emotional problems	0.01 (-0.07, 0.08)	-0.01 (-0.07, 0.08)
Conduct problems	0.04 (-0.01, 0.09)	0.04 (-0.01, 0.09)
Hyperactivity/ inattention	0.05 (-0.03, 0.12)	0.05 (-0.03, 0.12)
Peer problems	0.02 (-0.04, 0.08)	0.02 (-0.04, 0.08)
Prosocial skills	-0.02 (-0.08, 0.03)	-0.02 (-0.08, 0.03)

Note: SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00-24:00), 5 dB penalty for the evening noise (18:00-23:00) and 10 dB penalty for the night noise (23:00-07:00); ARTN (adjusted road traffic noise: modified L_{den} road traffic noise at home, based on information on bedroom orientation towards loudest street and whether or not the window was open or closed at night)

* adjusted for sex, age, drinking any alcohol, smoking, parents education, nationality, school level, physical activity, PM_{10}

**adjusted for sex, age, drinking any alcohol, smoking, screen time, parents education, nationality, school level, physical activity, PM_{10}, difference in height

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

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

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A R T I C L E I N F O

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A B S T R A C T

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.

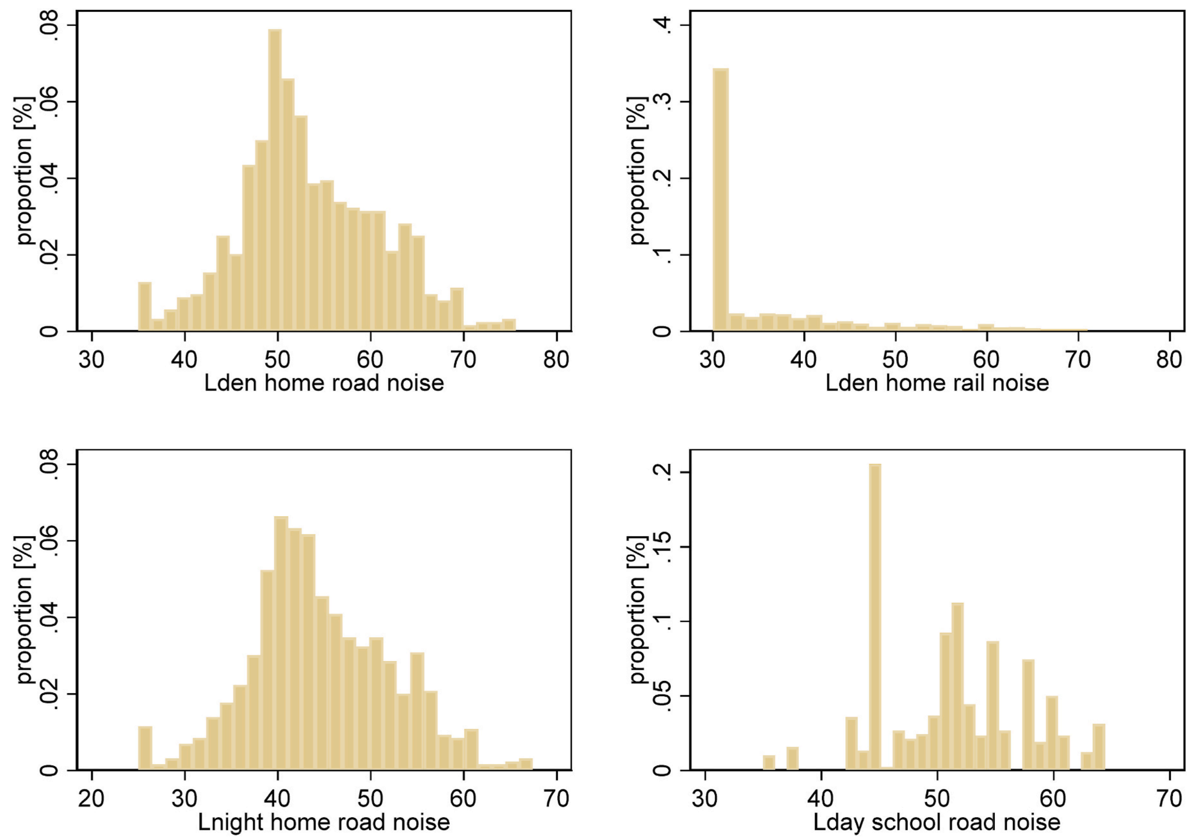

Fig. 1. Distribution of noise exposure metrics at home and at school. Note: L_{den} (00:00–24:00), with a 5 dB penalty for the evening noise (18:00–23:00) and 10 dB penalty for the night noise (23:00–07:00).

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

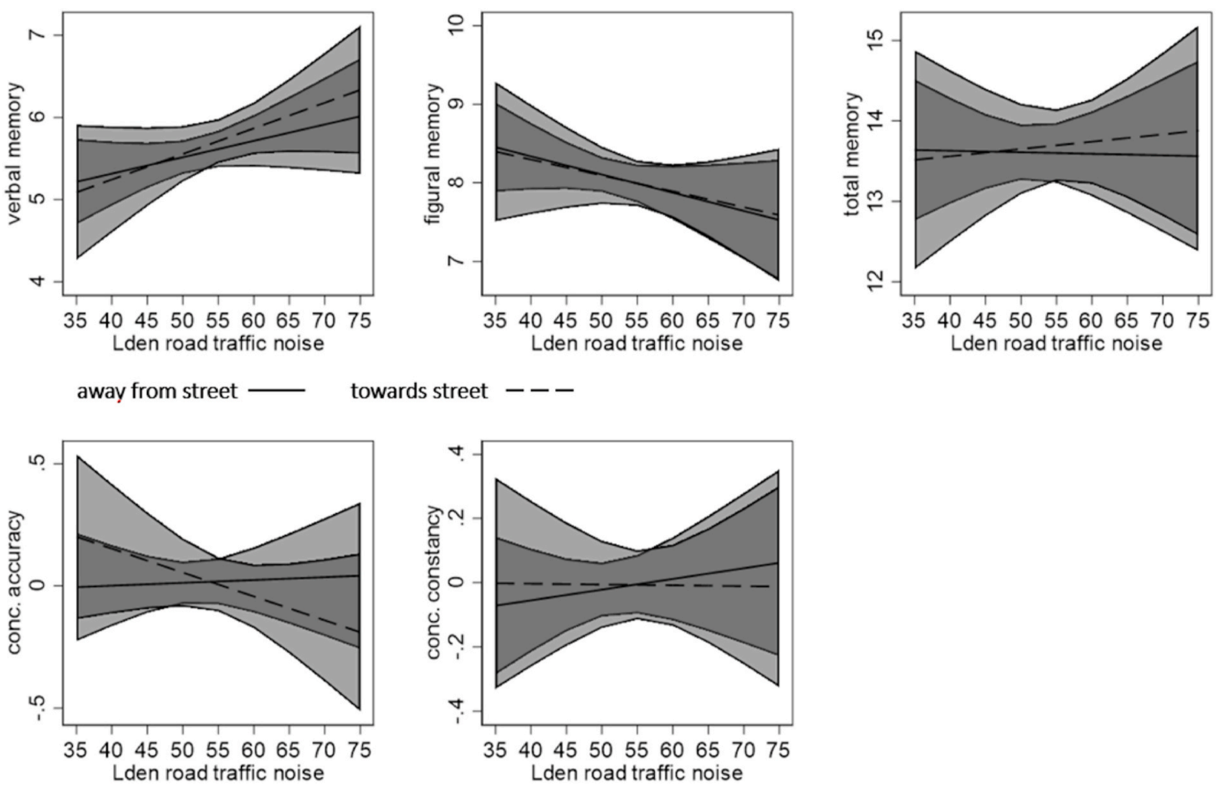

Fig. 2. Cross-sectional analyses: Associations of modelled road traffic noise in L_{den} at home and cognitive outcomes stratified by orientation to the street, using multilevel models, clustered by id for complete case analysis*

* 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.

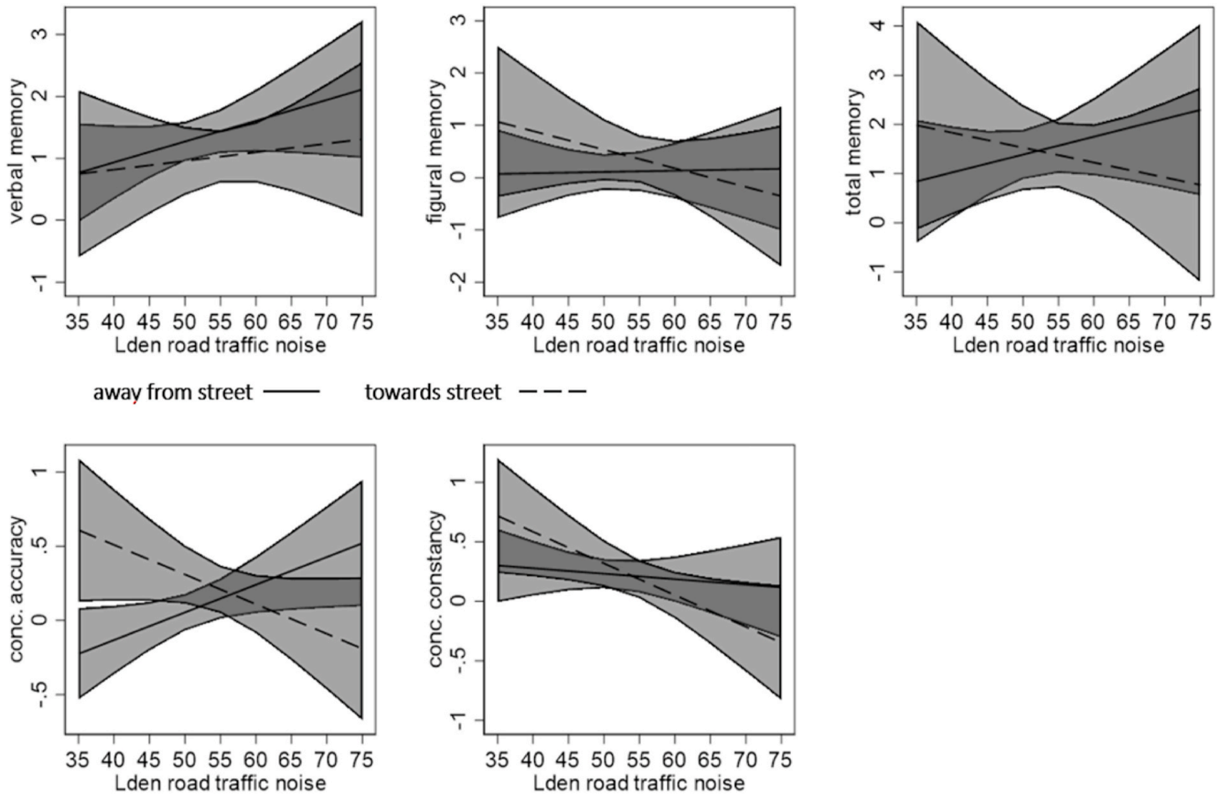

Fig. 3. Longitudinal analyses and interactions: Associations between road traffic noise in L_{den} at home and change of cognitive outcomes within a year stratified by bedroom orientation for complete case analysis*

* 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.

References

BAFU, 2009. SonBase - die GIS-Lärmdatenbank der Schweiz. Grundlagen. Umwelt-Wissen. Bern, Bundesamt für Umwelt, p. 61.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., Stansfeld, S., 2014. Auditory and non-auditory effects of noise on health. Lancet 383 (9925), 1325–1332.

Brickenkamp, R., 1962. Test D2: Aufmerksamkeits-Belastungs-Test. Verlag für Psychologie Hogrefe.

Brink, M., Schäffer, B., Vienneau, D., Pieren, R., Foraster, M., Eze, I.C., Rudzik, F., Thiesse, L., Cajochen, C., Probst-Hensch, N., 2019. Self-reported sleep disturbance from road, rail and aircraft noise: exposure-response relationships and effect modifiers in the SiRENE study. Int. J. Environ. Res. Publ. Health 16 (21), 4186.

Clark, C., Crombie, R., Head, J., Van Kamp, I., Van Kempen, E., Stansfeld, S.A., 2012. Does traffic-related air pollution explain associations of aircraft and road traffic noise exposure on children's health and cognition? A secondary analysis of the United Kingdom sample from the RANCH project. Am. J. Epidemiol. 176 (4), 327–337.

Clark, C., Martin, R., Van Kempen, E., Alfred, T., Head, J., Davies, H.W., Haines, M.M., Barrio, I.L., Matheson, M., Stansfeld, S.A., 2006. Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension: the RANCH project. Am. J. Epidemiol. 163 (1), 27–37.

Clark, C., Paunovic, K., 2018. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cognition. Int. J. Environ. Res. Publ. Health 15 (2), 285.

Connolly, D., Dockrell, J., Shield, B., Conetta, R., Mydlarz, C., 2019. The effects of classroom noise on the reading comprehension of adolescents 145 (1), 372–381.

Daiber, A., Kröller-Schön, S., Oelze, M., Hahad, O., Li, H., Schulz, R., Steven, S., Münzel, T., 2020. Oxidative stress and inflammation contribute to traffic noise-induced vascular and cerebral dysfunction via uncoupling of nitric oxide synthases. Redox Biol. 34, 101506.

EEA, 2020. Environmental Noise in Europe: 2020, vol. 1. European Environmental Agency, p. 104.

Empa, 2010. FLULA2, Ein Verfahren zur Berechnung und Darstellung der Fluglärmbelastung. Eidgenössische Materialprüfungs- und Forschungsanstalt (Empa), Dübendorf.

Evans, G.W., Stecker, R., 2004. Motivational consequences of environmental stress. J. Environ. Psychol. 24 (2), 143–165.

Foerster, M., Henneke, A., Mhlanga, S., Röösli, M., 2019. Impact of adolescents' screen time and nocturnal mobile phone related awakenings on sleep and non-specific health symptoms: a prospective cohort study. Int. J. Environ. Res. Publ. Health 16 (3), 518.

Fukuda, K., Ishihara, K., 2001. Age-related changes of sleeping pattern during adolescence. Psychiatr. Clin. Neurosci. 55 (3), 231–232.

Héritier, H., Vienneau, D., Foraster, M., Eze, I.C., Schaffner, E., Thiesse, L., Rudzik, F., Habermacher, M., Köpfli, M., Pieren, R., 2017. Transportation noise exposure and cardiovascular mortality: a nationwide cohort study from Switzerland. Eur. J. Epidemiol. 32 (4), 307–315.

Karipidis, I., Vienneau, D., Habermacher, M., Köpflii, M., Brink, M., Probst-Hensch, N., Röösli, M., Wunderli, J.-M., 2014. Reconstruction of historical noise exposure data for environmental epidemiology in Switzerland within the SiRENE project. Noise Mapp. 1 (2014), 3–14.

Klatte, M., Spilski, J., Mayerl, J., Möhler, U., Lachmann, T., Bergström, K., 2017. Effects of aircraft noise on reading and quality of life in primary school children in Germany: results from the NORAH study. Environ. Behav. 49 (4), 390–424.

Kontopantelis, E., White, I.R., Sperrin, M., Buchan, I., 2017. Outcome-sensitive multiple imputation: a simulation study. BMC Med. Res. Methodol. 17 (1), 2.

Krebs, W., Bütikofer, R., Plüss, S., Thomann, G., 2004. Sound source data for aircraft noise simulation. Acta Acustica united Acustica 90 (1), 91–100.

Liepmann, D., 2007. Intelligenz-Struktur-Test 2000 R: IST 2000 R (Hogrefe).

Lupien, S.J., Maheu, F., Tu, M., Fiocco, A., Schramek, T.E., 2007. The effects of stress and stress hormones on human cognition: implications for the field of brain and cognition. Brain Cognit. 65 (3), 209–237.

Matheson, M., Clark, C., Martin, R., Van Kempen, E., Haines, M., Barrio, I.L., Hygge, S., Stansfeld, S., 2010. The effects of road traffic and aircraft noise exposure on children's episodic memory: the RANCH Project. Noise Health 12 (49), 244.

Meteotest, 2017. Karten von Jahreswerten der Luftbelastung in der Schweiz. Datengrundlagen, Berechnungsverfahren und Resultaten der Karten bis zum Jahr 2016. Bern.

Moosbrugger, H.u., Goldhammer, F., 2007. Frankfurter Adaptiver Konzentrationsleistungs-Test (FAKT II). Auflage. Bern: Huber.

Papanikolaou, M., Skenteris, N., Piperakis, S., 2015. Effect of external classroom noise on schoolchildren's reading and mathematics performance: correlation of noise levels and gender. Int. J. Adolesc. Med. Health 27 (1), 25–29.

Roser, K., Schoeni, A., Bürgi, A., Röösli, M., 2015. Development of an RF-EMF exposure surrogate for epidemiologic research. Int. J. Environ. Res. Publ. Health 12 (5), 5634–5656.

Roser, K., Schoeni, A., Foerster, M., Röösli, M., 2016. Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour? Int. J. Publ. Health 61 (3), 307–315.

Schoeni, A., Roser, K., Röösli, M., 2015. Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: a prospective cohort study in adolescents. Environ. Int. 85, 343–351.

Shield, B., Conetta, R., Dockrell, J., Connolly, D., Cox, T., Mydlarz, C., 2015. A survey of acoustic conditions and noise levels in secondary school classrooms in England. J. Acoust. Soc. Am. 137 (1), 177–188.

Stansfeld, S., Clark, C., 2015. Health effects of noise exposure in children. Current environmental health reports 2 (2), 171–178.

Stansfeld, S., Hygge, S., Clark, C., Alfred, T., 2010. Night time aircraft noise exposure and children's cognitive performance. Noise Health 12 (49), 255.

Stansfeld, S.A., Berglund, B., Clark, C., Lopez-Barrio, I., Fischer, P., Öhrström, E., Haines, M.M., Head, J., Hygge, S., Van Kamp, I., 2005. Aircraft and road traffic noise and children's cognition and health: a cross-national study. Lancet 365 (9475), 1942–1949.

Thompson, R., Smith, R.B., Karim, Y.B., Shen, C., Drummond, K., Teng, C., Toledano, M. B., 2022. Noise pollution and human cognition: an updated systematic review and meta-analysis of recent evidence. Environ. Int. 158, 106905.

Van Kempen, E., Van Kamp, I., Lebret, E., Lammers, J., Emmen, H., Stansfeld, S., 2010. Neurobehavioral effects of transportation noise in primary schoolchildren: a cross-sectional study. Environ. Health 9 (1), 1–13.

van Kempen, E.E., 2008. Transportation Noise Exposure and Children's Health and Cognition. Utrecht University.

Vienneau, D., de Hoogh, K., Faeh, D., Kaufmann, M., Wunderli, J.M., Röösli, M., Group, S.S., 2017. More than clean air and tranquillity: residential green is independently associated with decreasing mortality. Environ. Int. 108, 176–184.
Vienneau, D., Héritier, H., Foraster, M., Eze, I.C., Schaffner, E., Thiesse, L., Rudzik, F., Habermacher, M., Köpfli, M., Pieren, R., 2019. Façades, floors and maps–Influence of exposure measurement error on the association between transportation noise and myocardial infarction. Environ. Int. 123 (2019), 399–406.
WHO, 2009. Night Noise Guidelines for Europe. WHO Regional Office Europe.

Supplements

Figure S1. Distribution of memory and concentration outcomes

Table S1. Noise exposure metrics by a selection of covariates at baseline

Table S2. Cross-sectional analyses and interactions: Associations of modelled road traffic noise in L_{den} road noise at home and cognitive outcomes with an interaction between noise and bedroom orientation using multilevel models, clustered by id

Table S3. Longitudinal analyses and interactions: Associations between road traffic noise in L_{den} at home and change of cognitive outcomes between baseline and follow-up with an interaction between road traffic noise in L_{den} exposure at home and bedroom orientation

Table S4. Associations between cognitive scores and L_{den} at home as well as L_{day} at school per 10dB for the cross-sectional and longitudinal analyses

Table S5. Cross-sectional analyses: Associations between either L_{den} road at home, L_{night} road at home, L_{day} road at school and L_{den} railway at home or L_{den} total (combination road, railway and aircraft noise) at home and cognitive scores using multilevel models, clustered by id

Table S6. Longitudinal analyses: Association of either L_{den} road at home, L_{night} road at home, L_{day} road at school and L_{den} railway at home or L_{den} total* with change in cognitive scores between baseline and follow-up

Table S7. Cross-sectional analysis: Comparison of analyses results using imputed data set with or without imputed outcome variables

Table S8. Longitudinal analysis: Comparison of analyses results using data set with or without imputed outcome variables

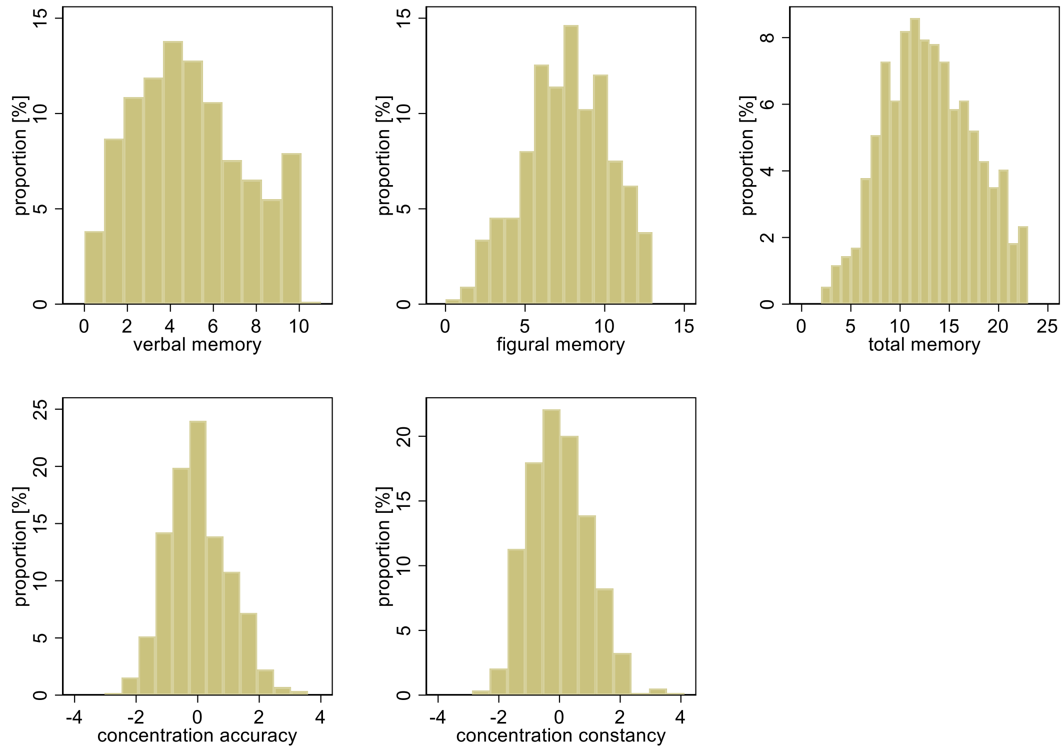

Figure S1. Distribution of memory and concentration outcomes

Table S1. Noise exposure metrics by groups of a selection of covariates at baseline*

	N	mean L_{den} road home(dB)	mean L_{den} rail home (dB)	mean L_{night} home (dB(A))	mean L_{den} school (dB)
Overall median of exposure		52	30	44	53
sex					
female	499	53	36	44	53
male	389	54	37	45	53
age					
<13	85	53	35	44	52
13 - <14	375	53	35	44	52
14 - <15	315	54	38	45	53
> 15	113	54	37	45	55
bedroom orientation					
missing	48	54	36	45	54
towards or side loudest street	319	56	37	48	53
away from loudest street	521	51	36	43	53
highest parents' education (lowest to highest)					
missing	167	56	37	47	53
no education	8	54	34	46	54
mandatory school	24	59	42	50	54
training school "Berufslehre"	301	53	36	45	53
secondary school "Gymnasium"	60	51	37	42	52
college of higher education "Fachhochschule"	253	52	35	43	53
university	75	52	36	44	53
school level of participants (lowest to highest)					
Secondary school C	168	56	37	47	53
Secondary school B	250	54	37	45	54
Secondary school A	288	52	36	43	52
"Gymnasium"	182	53	35	44	3
nationality of parents					
both Swiss	674	53	35	44	53
Swiss and other	126	55	38	47	54
both other	88	57	40	48	52

Note: L_{den} (00:00-24:00), with a 5dB penalty for the evening noise (18:00-23:00) and 10dB penalty for the night noise (23:00-07:00)
* Variable bedroom orientation reflects follow-up data, due to its use in model 3 of cross-sectional and longitudinal analyses.
Table represents data before imputation.

Table S2. Cross-sectional analyses with interactions: Associations of modelled road traffic noise at home in L_{den} and cognitive outcomes with an interaction between noise and bedroom orientation using multilevel models, clustered by id*. Interaction difference refers to change in score per 1dB for those with bedroom orientation.

	Indi-viduals	Obser-vations	L_{den} road traffic noise (10dB)	bedroom orientation	Interaction of road traffic noise + bedroom orientation
				Difference (95% CI)	
Verbal memory	845	1522	0.18 (-0.08, 0.43)	-0.14 (-2.24, 1.96)	0.00 (-0.04, 0.04)
Figural memory	844	1515	-0.25 (-0.53, 0.04)	0.17 (-2.13, 2.47)	0.00 (-0.05, 0.04)
Total memory	843	1508	0.07 (-0.49, 0.36)	0.12 (-3.36, 3.61)	0.00 (-0.07, 0.06)
Concentration accuracy	788	1253	0.01 (-0.10, 0.12)	0.66 (-0.20, 1.52)	**-0.01 (-0.03, 0.00)**
Concentration constancy	788	1253	0.03 (-0.07, 0.14)	0.48 (-0.38, 1.33)	0.01 (-0.02, 0.01)

Note: L_{den} (00:00-24:00), 5dB penalty for the evening noise (18:00-23:00) and 10dB penalty for the night noise (23:00-07:00); L_{day} (7:00-23:00); L_{den} total: combined L_{den} of road traffic, railway and aircraft noise; PM_{10}: particular matter 10 micrometers and smaller; NDVI: normalized difference vegetation index; EMF: electromagnetic field (see (Roser et al., 2015) for dosimetric model)

* Model adjusted for sex, age, drinking any alcohol, smoking, parents' education, nationality, school level, physical activity, screen time, PM_{10}, NDVI, EMF, bedroom orientation

Table S3 Longitudinal analyses with interactions: Associations between road traffic noise in L_{den} at home and change of cognitive outcomes between baseline and follow-up with an interaction between road traffic noise in L_{den} exposure at home and bedroom orientation**. Interaction difference refers to change in score per 1dB for those with bedroom orientation.

	N	L_{den} road noise (10dB)	bedroom window orientation	Interaction of road noise + bedroom orientation
			Difference (95% CI)	
Verbal memory	677	0.13 (-0.28, 0.53)	0.59 (-2.95, 4.13)	-0.02 (-0.08, 0.05)
Figural memory	671	-0.03 (-0.47, 0.41)	1.18 (-2.65, 4.95)	-0.02 (-0.09, 0.05)
Total memory	665	0.13 (-0.52, 0.78)	2.13 (-3.54, 7.78)	-0.04 (-0.15, 0.06)
Concentration accuracy	465	0.12 (-0.04, 0.27)	**1.61 (0.23, 2.98)**	**-0.03 (-0.05, 0.00)**
Concentration constancy	465	-0.04 (-0.20, 0.12)	1.21 (-0.19, 2.60)	**-0.02 (-0.05, 0.00)**

Note: L_{den} (00:00-24:00), 5dB penalty for the evening noise (18:00-23:00) and 10dB penalty for the night noise (23:00-07:00); L_{day} (7:00-23:00); L_{den} total: combined L_{den} of road traffic, railway and aircraft noise; PM_{10}: particular matter 10 micrometers and smaller; NDVI: normalized difference vegetation index; EMF: electromagnetic field (see (Roser et al., 2015) for dosimetric model)

* Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, participants' school level, physical activity, PM_{10}, bedroom orientation towards street

Table S4. Associations between cognitive scores and L_{den} at home as well as L_{day} at school per 10dB using multilevel models, clustered by id (cross-sectional) and change in cognitive scores between baseline and follow-up (longitudinal)

	N		Cross-sectional analyses*	Longitudinal analyses**	
	Indiv-iduals	observ ations	Difference (95% CI)	N	Difference (95% CI)
Memory verbal					
L_{den} road traffic noise at home (10dB)	845	1522	0.18 (-0.02, 0.39)	677	0.01 (-0.30, 0.32)
L_{day} road traffic noise at school (10dB)			-0.11 (-0.35, 0.13)		0.10 (-0.29. 0.50)
Memory figural					
L_{den} road traffic noise at home (10dB)	844	1515	**-0.27 (-0.49, -0.05)**	671	-0.08 (-0.41, 0.25)
L_{day} road traffic noise at school (10dB)			0.18 (-0.09, 0.45)		-0.03 (-0.45, 0.39)
Memory total					
L_{den} road traffic noise at home (10dB)	843	1508	-0.09 (-0.43, 0.25)	665	-0.09 (-0.58, 0.41)
L_{day} road traffic noise at school (10dB)			0.06 (-0.35, 0.48)		0.09 (-0.53, 0.72)
Concentration accuracy					
L_{den} road traffic noise at home (10dB)	788	1253	-0.05 (-0.13, 0.04)	465	0.02 (-0.11, 0.14)
L_{day} road traffic noise at school (10dB)			0.07 (-0.03, 0.18)		-0.04 (-0.19, 0.12)
Concentration constancy					
L_{den} road traffic noise at home (10dB)	788	1253	-0.09 (-0.43, 0.25)	465	**-0.13 (-0.25, 0.00)**
L_{day} road traffic noise at school (10dB)			0.06 (-0.04, 0.16)		0.07 (-0.08, 0.23)

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

* adjusted for sex, age, drinking any alcohol, smoking, parents' education, nationality, school level, physical activity, screen time, $PM_{10,}$ NDVI, EMF

** adjusted for sex, age, drinking any alcohol, smoking, parents' education, nationality, school level, physical activity, screen time, $PM_{10,}$ NDVI, EMF, difference in height between baseline and follow-up

Table S5. Cross-sectional analyses: Associations between either L_{den} road at home, L_{night} road at home, L_{day} road at school and L_{den} railway at home or L_{den} total (combination road, railway and aircraft noise) at home and cognitive scores using multilevel models, clustered by id

	N		L_{den} road at home (model 2 in table 3)	L_{night} road at home	L_{day} road at school	L_{den} railway at home	L_{den} total at home ***
	Indi-vid-uals	Ob-serva-tions	Increase L_{den} by 10dB	Increase L_{night} by 10dB(A)	Increase L_{day} by 10dB(A)	Increase L_{den} by 10dB	Increase L_{den} by 10dB
Memory verbal	845	1522	0.18 (-0.02, 0.38)	0.18 (-0.02, 0.38)	-0.11 (-0.35, 0.14)	-0.03 (-0.19, 0.12)	0.15 (-0.04, 0.35)
Memory figural	844	1515	**-0.27 (-0.49, -0.04)****	**-0.27 (-0.49, -0.04)****	0.17 (-0.10, 0.44)	-0.03 (-0.20, 0.14)	-0.20 (-0.42, 0.01)
Memory total	843	1508	-0.09 (-0.43, 0.25)	-0.09 (-0.43, 0.25)	0.06 (-0.35, 0.47)	-0.07 (-0.33, 0.19)	-0.06 (-0.29, 0.27)
Concen-tration accuracy	788	1253	-0.04 (-0.13, 0.04)	-0.04 (-0.13, 0.04)	0.07 (-0.03, 0.17)	0.00 (-0.06, 0.07)	-0.04 (-0.12. 0.04)
Concen-tration constancy	788	1253	0.00 (-0.09, 0.08)	0.00 (-0.09, 0.08)	0.06 (-0.04, 0.16)	0.01 (-0.05, 0.08)	-0.01 (-0.09, 0.07)

Note: L_{den} (00:00-24:00), 5dB penalty for the evening noise (18:00-23:00) and 10dB penalty for the night noise (23:00-07:00); L_{day} (7:00-23:00); PM_{10}: particular matter 10 micrometers and smaller; NDVI: normalized difference vegetation index; EMF: cumulative electromagnetic field brain dose (see (Roser et al., 2015) for dosimetric model)

* Model adjusted for sex, age, drinking any alcohol, smoking, parents' education, nationality, school level, physical activity, screen time, PM_{10}, NDVI, EMF
** results of L_{night} and L_{den} road traffic noise differences for all outcomes after are the same rounding due to the strong correlation between exposures

*** L_{den} total: combined L_{den} of road traffic, railway and aircraft noise.

Table S6. Longitudinal analyses: Association of either L_{den} road at home, L_{night} road at home, L_{day} road at school and L_{den} railway at home or L_{den} total* with change in cognitive scores between baseline and follow-up**

	N	L_{den} road at home (model 2 in table 3)	L_{night} road at home	L_{day} road at school	L_{den} railway at home	L_{den} total at home
		Increase L_{den} by 10dB	Increase L_{night} by 10dB(A)	Increase L_{day} by 10dB(A)	Increase L_{den} by 10dB	Increase L_{den} by 10dB
Memory verbal	845	0.01 (-0.30, 0.32)	0.01 (-0.30, 0.31)	0.10 (-0.29, 0.49)	-0.14 (-0.38, 0.10)	0.03 (-0.27, 0.33)
Memory figural	844	-0.08 (-0.41, 0.25)	-0.08 (-0.41, 0.24)	-0.03 (-0.45, 0.39)	-0.06 (-0.31, 0.19)	-0.11 (-0.42, 0.21)
Memory total	843	-0.09 (-0.58, 0.41)	-0.09 (-0.58, 0.40)	0.09 (-0.54, 0.71)	-0.23 (-0.61, 0.15)	-0.09 (-0.57, 0.38)
Concentration accuracy	788	0.02 (-0.11, 0.14)	0.01 (-0.11, 0.13)	-0.04 (-0.19, 0.12)	-0.06 (-0.15, 0.04)	-0.01 (-0.13, 0.11)
Concentration constancy	788	**-0.13 (-0.25, 0.00)**	**-0.13 (-0.25, 0.00)**	0.07 (-0.09, 0.22)	-0.09 (-0.18, 0.00)	**-0.15 (-0.26, -0.03)**

Note: L_{den} (00:00-24:00), 5dB penalty for the evening noise (18:00-23:00) and 10dB penalty for the night noise (23:00-07:00); L_{day} (7:00-23:00); L_{den} total: combined L_{den} of road traffic, railway and aircraft noise; PM_{10}: particular matter 10 micrometers and smaller; NDVI: normalized difference vegetation index; EMF: cumulative electromagnetic field brain dose (see (Roser et al., 2015) for dosimetric model)

* L_{den} total: combined L_{den} of road traffic, railway and aircraft noise.
** Model adjusted for sex, age, drinking any alcohol, smoking, parents' education, nationality, school level, physical activity, screen time, PM_{10}, NDVI, EMF, difference in height

Table S7. Cross-sectional analyses: Comparison of analyses results using imputed data set with or without imputed outcome variables

	Data set imputed then outcome variables deleted for analyses		Data set imputed and fully used in analyses	
		Increase L_{den} by 10dB		Increase L_{den} by 10dB
	N	Difference (95%CI)	N	Difference (95%CI)
Memory verbal	1522	0.18 (-0.02, 0.38)	1776	0.17 (-0.03, 0.37)
Memory figural	1515	**-0.27 (-0.49, -0.04)**	1776	**-0.25 (-0.48, -0.02)**
Memory total	1508	-0.09 (-0.43, 0.25)	1776	-0.08 (-0.43, 0.27)
Concentration accuracy	1253	-0.04 (-0.13, 0.04)	1776	-0.04 (-0.13, 0.05)
Concentration constancy	1253	0.00 (-0.09, 0.08)	1776	0.01 (-0.08, 0.09)

Note: L_{den} (00:00-24:00), 5dB penalty for the evening noise (18:00-23:00) and 10dB penalty for the night noise (23:00-07:00);

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

Table S8. Longitudinal analysis: Comparison of analyses results using imputed data set without or with imputed outcome variables

	Data set imputed then outcome variables deleted for analyses		Data set imputed and fully used in analyses	
		Increase L_{den} by 10dB		Increase L_{den} by 10dB
	N	Difference (95%CI)	N	Difference (95%CI)
Memory verbal	677	0.01 (-0.30, 0.32)	888	0.05 (-0.25, 0.35)
Memory figural	671	-0.08 (-0.41, 0.25)	888	-0.14 (-0.45, 0.18)
Memory total	665	-0.09 (-0.58, 0.41)	888	-0.09 (-0.56, 0.38)
Concentration accuracy	465	0.02 (-0.11, 0.14)	888	-0.01 (-0.15, 0.12)
Concentration constancy	465	**-0.13 (-0.25, 0.00)**	888	-0.11 (-0.25, 0.03)

Note: L_{den} (00:00-24:00), 5dB penalty for the evening noise (18:00-23:00) and 10dB penalty for the night noise (23:00-07:00)

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

6. Summary of the main findings

Objective 1. Analyse the association between transportation noise and adolescent cognitive functions or behaviour problems.

Study 1: In cross-sectional analyses an association was found between peer relationship problems and road noise exposure at home. The longitudinal analyses, based on the change in outcome after one year, did not show associations between road noise exposure at home and any of the investigated behaviours.

The expected association of noise with hyperactivity/inattention found in other studies was not found with modelled noise exposures at home or at school.

Study 2: In cross-sectional analyses significantly lower figural memory were found in adolescents that were exposed to more road noise traffic at home. This association was not found in longitudinal analyses, whereas concentration constancy was significantly associated with noise, particularly for participants sleeping towards the noisiest street passing by the house.

Conclusion: Slight indications were found of positive associations of road traffic noise exposure with behavioural and cognitive outcomes. The association with peer relationship problems was particularly novel, being previously reported only in one study. Of five cognitive outcomes, associations were only found for one in cross-sectional analyses (figural memory) and one in longitudinal analyses (concentration constancy).

Objective 2. Describe and quantify the role of transportation noise at home, at school and their relationship.

Study 1: In cross-sectional 2-pollutant multilevel models, an association was found between road noise at home with peer relationship. In the same models road noise exposure at school (L_{den}) was twice associated inversely to what had been expected – less peer problems and more prosocial skills with higher road noise exposure at school.

Study 2: In both longitudinal and cross-sectional 2-pollutant models, the same associations were found for road noise at home as in the main analysis. In these models day road noise at school (L_{day}) showed no independent associations with any cognitive outcomes.

Conclusion: Due to high possibility of misclassifications of the school noise exposure for road traffic noise, in particular, I consider the results for school noises association limited. Thus, it is not possible to draw clear conclusions on the relationship between noise at home and school. The topic of school road noise exposure classification is commented on further in the discussion part of this thesis.

Objective 3. Evaluate the role of different noise characteristics in impacting health outcomes.

Study 1: In cross-sectional analyses, neither the IR, nor the N_{evt} showed associations with the health outcomes. Road noise at home for L_{den} or L_{night} showed nearly exactly the same associations with the outcomes.

Study 2: In both cross-sectional and longitudinal analyses, the L_{den} and L_{night} metrics at home were so similar, the associations expressed per 10 dB were identical to the second decimal place. Analyses not included in the paper (presented in this thesis discussion), showed no associations between IR and N_{evt} with the cognitive outcomes.

Conclusion: Associations of IR and N_{evt} with behavioural or cognitive outcomes were not found in our studies. The difference between using metrics representing 24 hour noise exposure (L_{den}) or specific times of day (L_{day}, L_{night}) did not change the measured associations by much probably due to the high correlations between metrics.

Objective 4. Use parameters that modify transportation noise reaching the participants, such as bedroom orientation towards the loudest side of the house, and determine their role in noise exposure.

Study 1: An unexpected association was found between the bedroom orientation and hyperactivity/inattention, conduct problems and SDQ total difficulties in cross-sectional and only with hyperactivity/inattention in the longitudinal analyses. This association was independent from the modelled noise exposure. Stratification did not show that participants sleeping towards the loudest street by the house showed different associations between noise exposure and outcome.

Study 2: Cross-sectional analyses show that for concentration accuracy, people sleeping towards the loudest street by the house were more negatively affected by the modelled noise. The calculated interaction term was significant. In longitudinal analyses the same difference was visible for four of five outcomes in the stratified graphs for the association between noise and figural memory, total memory, and concentration accuracy and constancy. However, the interaction terms were only significant for the two concentration outcomes.

Conclusion: Study 1 did not give a clear answer to the usefulness of the variable bedroom orientation in the main noise-outcome model, but did show independent associations with the outcomes; this needs to be further explored with more studies. Study 2 showed associations in the expected direction for only people sleeping towards the loudest street by the house, as well as interactions. These associations could be seen on graphs, but were not significant and need to be reaffirmed with studies of higher power. Strikingly the longitudinal analysis indicated associations and would mean a noticeable change of cognition though only one year of higher noise exposure.

7. General discussion and conclusion

Detailed discussions on results can be found in the individual papers. The following sections contain some additional thoughts and analyses that where over and above the scope of the papers.

7.1 Representing reality

One of the most challenging aspects of epidemiological work is to obtain data that reflects reality as closely as possible. The variables and data used in these studies cannot be more than proxies for the parameters that were attempted to measure, be it data resulting from self-assessments collected through questionnaires (eg. the SDQ for behavioural data), testing with software programs (eg. the FAKT-II, d2, IST-Test for cognitive data) or the use of models to build road traffic noise maps.

Some things are more easily measured, such as age and sex, and psychological testing tools underwent thorough developmental steps for validity and usability. The noise maps used in this dissertation are considered gold standard exposure models (Vienneau et al., 2019) based on three-dimensional source-propagation noise models. The available different metrics even allow – as seen in the analysis – to describe details about the quality of noise beyond average levels, such as the amount of loud noise events.

Still, some of the data and measures obtained will continue to fall short of the desired reliability, while it may be possible to optimize others in order to reflect the true object measured.

7.1.1 Bedroom orientation

Data on the variable bedroom orientation was collected during the study to learn about the noise exposure of participants at night. The modelled road noise variable used in the studies represents the loudest façade of the house. If modelled perfectly, the variable would represent the level of traffic noise reaching a person's bedroom façade if they indicated sleeping towards the loudest street passing by their residence.

Using the variable in models on behaviour and behaviour change led to unexpected findings. An independent association was found between the variable bedroom orientation with the outcome hyperactivity/inattention. Adolescents sleeping towards the loudest street by the house had more hyperactivity. But this finding was independent of the modelled noise. The association did not show even when stratifying the noise-behavioural outcome by bedroom orientation.

In the first study additional sensitivity analyses were run using estimations (Locher et al., 2018) on how much the noise was dampened from the loudest façade point to the inside of the room by location of the bedroom and whether or not the window was open. Conducting the additional sensitivity analyses did not, however, provide any additional insight.

In the second study, the expected interaction was found between level of noise exposure and bedroom orientation for concentration accuracy in cross-sectional analyses and both concentration variables in longitudinal analyses. Visual depiction of stratified associations by bedroom orientation allowed to detect associations for participants sleeping towards the louder street, which had not been previously significant or visible.

These results show that the bedroom orientation variable should be used in any study on the impact of road traffic noise at home (if it can be collected). Doing this would allow to further optimize noise modelling and to disentangle the effects of noise pollution at home.

7.1.2 Road noise at schools

In this dissertation, noise exposure at the school location did not show significant associations with the outcome. In both studies the difficulty is discussed of modelling actual road traffic noise exposure for the students while at school.

The following reasons might have affected the validity of the school exposure data, likely through increased exposure misclassification:

Per school, one address point was available, which allowed us to extract data for the loudest façade point of a building. Schools mostly covered relatively large areas and consisted of at least one, sometimes several large buildings. Theoretically, the noise maps would have allowed us to model more locations, but specific information was lacking about the locations of students and their classrooms.

In order to ascertain information about the variability of noise exposure within schools, conducted a sensitivity analysis was conducted, using a raster noise map (raster resolution 10x10m) from the Federal Office of Topography swisstopo (map.geo.admin.ch). Out of the 45 schools attended by study participants, 17 had no variability in road noise exposure, 20 had some variability and 8 had strong variability in road noise exposure. Figure 4 shows an example of a large school building with much variability in noise exposure. The side of the building facing South-East has estimated noise levels between 45-49.9 dB, while the most exposed façade on the other side has levels up to 70-74.9 dB.

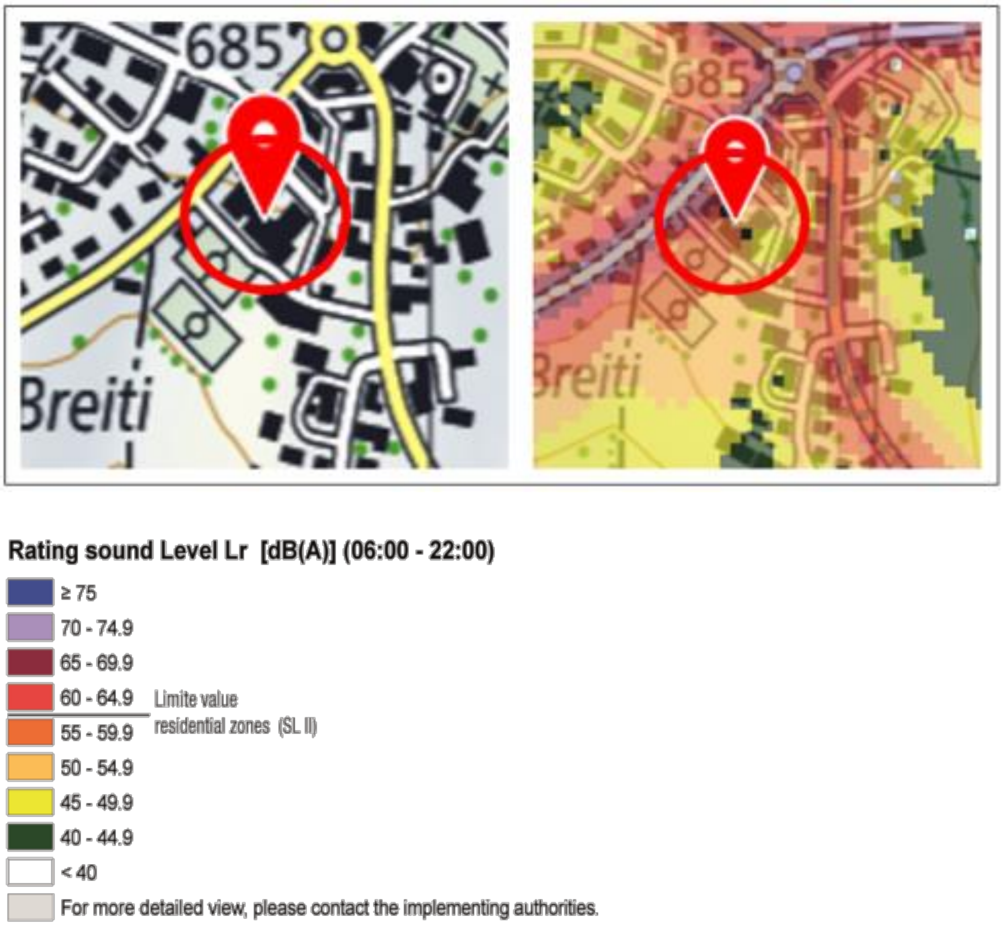

Figure 4. Road traffic noise levels (dB) of an example school with a high noise variability.

Another reason for possible exposure misclassification is the movement of students within and between buildings, when visiting different classes. This is especially true for secondary school students, who have more complex and diverse curriculums compared to, for example, primary school students. As a result, measurements for one room or one façade point on the building may not sufficiently represent a student's exposure to noise indoors.

Depending on available time and resources, future studies should collect additional data on course / class timetables, as well as details on the geo-location and floor levels of classrooms. Collection of individual class timetable information, with location and floor level, for each participant, will facilitate to define more precisely the noise maps, i.e the exposure for all classrooms, and for individual study participants.

Another very specific problem with true road noise exposure in schools is that the noise that reaches the inside of the classroom might not be loud enough to affect students. A study found average noise levels in schools around 64 dB(A) (Shield et al., 2015). Our mean noise levels for schools were at 52.6 dB (L_{den}). This might indicate that the sound level inside schools might still not be noisy enough to mask outside road noise.

Another factor might also limit outside traffic noise from reaching the inside of school buildings. School buildings in areas with particularly high levels of road traffic noise, may have already established preventive measures, eg. the installation of double or triple glazed windows.

Combining all these arguments, the chances of detecting effects on children and adolescents health from continuous, but low-level road noise exposure seem less likely than finding such health impact for aircraft noise (being very loud, intermittent and potentially disruptive to learning).

7.1.3 The hen and the egg

There are two main scenarios where noise might affect health, behaviour and/or cognition in children: 1. through disturbing sleep, or 2. by disturbing learning processes (predominantly, but not exclusively, through noise exposure at school). Both noise exposure scenarios - exposure at home or at school - might induce increased hyperactivity/attention problems, which in turn will negatively impact on academic performance (Figure 5). Three studies found associations between road traffic noise at home and the behavioural outcome hyperactivity/inattention (Hjortebjerg et al., 2016; Tiesler et al., 2013; Weyde et al., 2017), but they did not measure cognitive outcomes.

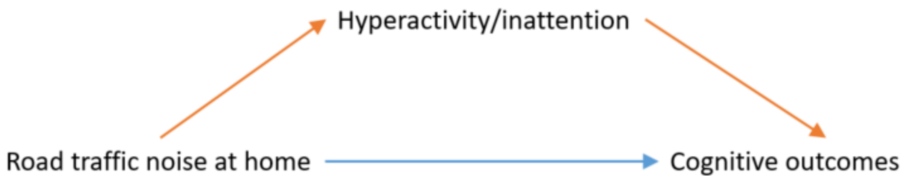

Figure 5. Possible pathway between noise exposure and two outcomes (hyperactivity/inattention and cognition)

This dissertation showed a link between being exposed to the loudest street by the house and hyperactivity/inattention. It also showed an association between modelled higher road traffic noise with worse cognitive outcomes, without seeing this association for aircraft, rail or road traffic noise with either hyperactivity/inattention or cognitive functions. The association found for noise and hyperactivity/inattention was not based on the modelled noise exposure, but the variable bedroom orientation towards the loudest street by the house. Therefore, more studies are needed to confirm these findings, by showing that road traffic at noise might affect students more by heightening hyperactivity/inattention and then influencing cognitive outcomes.

7.1.4 IR and Nr_{evt}

Sensitivity analyses were conducted in both studies looking at the association between event-based noise metrics. These sensitivity results were not included in the second study paper and are therefore presented them here (Table 1 and 2). Over both studies, no associations were found either for the intermittency ratio, or for the Number of events metric. The most likely explanation is that the constant flow of traffic on major roads, by nature, produces less intermittent but more continuous noise. The exposure used did not have many noise “events” to stand out, thus these results indicate the equivalent sound metrics could be sufficient to measure health-related outcomes for road traffic noise.

Table 1. Secondary cross-sectional and longitudinal analysis: 2-pollutant analysis with Lden road at home and Intermittency Ratio (IR) for road at home

	Cross-sectional multilevel analyses		Longitudinal change score analysis	
	L_{den} road traffic noise at home per 10 dB	IR* of road traffic noise at home	L_{den} road traffic noise at home per 10 dB	IR* of road traffic noise at home
	Coefficient (95% CI)			
Memory verbal	0.17 (-0.03, 0.38)	1.86 (-3.85, 7.57)	-0.01 (-0.32, 0.31)	3.04 (-5.82, 11.89)
Memory figural	**-0.28 (-0.50, -0.05)**	3.07 (-1.20, 9.33)	-0.11 (-0.44, 0.22)	5.45 (-3.93, 14.83)
Memory total	-0.12 (-0.46, 0.23)	5.04 (-4.58, 14.67)	-0.13 (-0.63, 0.37)	9.15 (-4.86, 23.16)
Concentration accuracy	-0.04 (-0.13, 0.05)	-0.68, (-3.11, 1.75)	0.00 (-0.12, 0.13)	2.10 (-1.21, 5.40)
Concentration constancy	0.00 (-0.09, 0.09)	-0.42 (-2.82, 1.98)	**-0.15 (-0.27, -0.02)**	3.54 (-0.21, 6.88)

Note: Significant results at the 95% CI level are highlighted in bold; SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00-24:00), 5 dB penalty for the evening noise (18:00-23:00) and 10 dB penalty for the night noise (23:00-07:00); L_{day} (7:00-23:00); IR: Intermittency Ratio

Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents’ education, nationality, school level, physical activity, PM_{10}

* Coefficient multiplied by 1000

Table 2. Secondary cross-sectional and longitudinal analysis: 2-pollutant analysis with Lden road at home and Number of events

	Cross-sectional multilevel analyses		Longitudinal change score analysis	
	L_{den} road traffic noise at home per 10 dB	Number of events* of road traffic noise at home	L_{den} road traffic noise at home per 10 dB	Number of events* of road traffic noise at home
	Coefficient (95% CI)			
Memory verbal	0.17 (-0.10, 0.44)	0.03 (-0.27, 0.31)	-0.11 (-0.52, 0.31)	0.18 (-0.25, 0.61)
Memory figural	**-0.40 (-0.70, -0.10)**	0.22 (-0.09, 0.53)	-0.12 (-0.56, 0.33)	0.06 (-0.40, 0.52)
Memory total	-0.25 (-0.71, 0.20)	0.27 (-0.21, 0.74)	-0.23 (-0.89, 0.43)	0.22 (-0.46, 0.91)
Concentration accuracy	0.02 (-0.10, 0.14)	-0.10 (-0.22, 0.02)	0.08 (-0.09, 0.24)	-0.10 (-0.28, 0.08)
Concentration constancy	0.03 (-0.09, 0.14)	-0.05 (-0.17, 0.08)	-0.09 (-0.25, 0.08)	-0.06 (-0.02, 0.12)

Note: Significant results at the 95% CI level are highlighted in bold. SDQ, Strengths and Difficulties Questionnaire; L_{den} (00:00-24:00), 5 dB penalty for the evening noise (18:00-23:00) and 10 dB penalty for the night noise (23:00-07:00); L_{day} (7:00-23:00)
Model adjusted for: sex, age, drinking any alcohol, smoking, screen time, parents' education, nationality, school level, physical activity, PM_{10}
* Coefficient multiplied by 1000

7.2 Methods

7.2.1 Multiple imputation

Multiple imputation technique (Abbr.: MI) was chosen to impute missing observations. It is a method that uses all available information in the data to create plausible complete data sets.

The first phase of the MI process is the imputation or fill-in phase: regressions are run on the existing data to fill in missing data points one by one until one complete data set is produced. This process is repeated multiple times – often 20 or 25 – each time producing a separate completed data set. In the analysis phase, each of these complete data sets are analysed. Then, in the pooling phase, the parameter estimates are consolidated.

Compared to other imputation methods which generate single imputed data points (which are then treated as observed data), the MI method allows for uncertainty in its imputed values. Compared to the complete case analysis, the advantage of the MI method is that participants with missing values are not ignored in the final analysis – valuable information is not lost. This reduces potential selection bias, as the reason for missing values in a particular variable might be particular to a specific trait common to a group of participants.

An example from our study: "parent's education" was one of the best proxies for socioeconomic status in our data set. However, there was a high volume of missing data because this variable stemmed from a questionnaire given to the participants parents, for which the return rate was lower compared to the return rate from participants themselves. By including many informing auxiliary variables in the fill-in phase of the MI (including for example the school level of participants) made it possible to impute values for the parent's education variable where this was missing; this also allowed to preserve data on parent's education which was actually collected.

7.3 Future studies

If the results of epidemiological studies point to a health threat as being relevant and needing to be addressed with public health measures, it is important to first define and then quantify this threat.

Several systematic reviews have been recently conducted on the association between noise and behavioural or cognitive health (Clark & Paunovic, 2018; Schubert et al., 2019; Thompson et al., 2022). The quantification of the results with meta-analyses have been shown to be difficult, as the methods, including study design, outcomes (choice of cognitive tests) and choice of confounders are varied and not easily combined. Two meta-analyses are presented in the introduction of this thesis. Both used three different studies each to calculate an estimation of how the outcome hyperactivity/inattention is affected by noise. One used studies with linear effect estimates of noise and the hyperactivity score (range 0-10) (Clark et al., 2021). The other meta-analysis used studies whose results were odds ratios, based the association between noise and the categorized hyperactivity variable ("normal", " borderline", "abnormal") (Schubert et al., 2019). There are arguments on both sides for choosing either a continuous or a categorical version of a variable.

7.3.1 Behavioural problems

For the outcome, using categorical outcomes allows the researcher to say something about the risk for participants to develop symptoms that are classically connected to diagnoses. On the other hand the continuous variable is more sensitive to any change (positive or negative) and might allow insights impossible to find if participants are grouped by category. This is particularly relevant for in the field of environmental epidemiology, where there are situations that require analyses to detect very small associations between exposures and outcomes. These associations and potential effects might be small, but very relevant for Public Health if the exposure affects the majority or big parts the population: like environmental noise.

7.3.2 Noise maps

In the case of noise mapping, different levels of detail are possible. A lot of countries in Europe base their noise modelling on the requirements of the Environmental Noise Directive (END) requiring noise maps for noise above 55 dB L_{den} and 50 dB L_{night}. That means that this particular cut has been established in a lot of studies as a threshold of measuring health effects. But, since then studies have shown impact of environmental noise exposure from 40 dBs onward (Héritier et al., 2017).

7.3.3 Exposure assessment in schools

If road traffic noise penetrating buildings is assessed, it is important to collect as much data as possible about the locations of participants inside buildings. For aircraft noise this is not as important, as it originates above and affects broader areas compared to road noise. If possible, researchers or study support staff visiting the schools should undertake a basic assessment to collect information about the extent of noise-insulation of buildings: number of layers of glass in windows, window frame material, age of building, construction type and building material used, and history of possible renovations.

7.3.4 Bedroom orientation

In any study including noise exposure at home, (especially road noise) questionnaires for children and/or parents should include a question on the orientation of bedrooms and their windows relative to the loudest street passing by the house. The researchers collected HERMES-data in the second wave noted that a few students had problems answering the question "does your bedroom face a street" (yes / no), as participants sometimes felt the answers provided were not relevant for their living situation. Brink et al. (2019) used three answering options (away or to a backyard / towards the side / towards the street). In order to allow for any potential living situation, the following addition should be added as well: "there is no busy street by the house".

While conducting the analyses and interpreting data, another variable seemed important particularly for adolescents. Where in the house do adolescents do their homework? This, as well as information about the location of the room, would be a useful addition to any future study, especially on the topic of noise impact on cognitive outcomes.

7.3.5 Harmonization

As it is in the interest of all researchers to combine forces and provide high quality evidence to stakeholders, my proposition would be to for epidemiologists studying the impact of noise on health to agree on standardized noise analyses and either present these as a main component of the paper or add them as supplementary material. These standards could include specific thresholds for noise exposures (such as the END requirements). If possible, it would be good to agree on outcome measures as well. For the assessment of behavioural outcomes, the SDQ seems to already be a predominantly used tool, available in various languages. For the more complicated situation of cognitive functions, there needs to be a discussion between researchers on possible solutions. A list of minimal or core and "nice to have", requirements would facilitate the negotiations. Core requirements might include: validity, availability in various languages, accessibility, price, usability etc.

The reason why I do not propose every study to follow strict protocol as their main analysis is, that it would limit the possibilities, creativeness and progressiveness of conducting studies. For example, in the case of noise modelling, if available, the lower decibel ranges are important to explore and learn about to further noise and maybe adapt the END in the coming years. However, there is a need to combine knowledge, heighten explanatory power of effect estimations of noise exposure, through meta-analyses of as many studies as possible. This requires standardized analyses to be run and be made available, if only as supplementary material.

7.4 Secondary data analysis

The data used in this dissertation had originally been collected for and used in the HERMES-study. As mentioned in the introduction, HERMES assessed the impact of mobile phone use on adolescents. Three PhD students developed the methods for data collection and collected the data starting with the first wave in 2012 (N_{wave1}: 442, two responsible PhDs) and the second wave of the study in 2014 (N_{wave2}: 457, one responsible PhD). Before any concrete plans had been made to study the impact of noise exposure on participants, Martin Röösli, the supervisor and grant receiver of the HERMES study had integrated questions into the questionnaire that were relevant for noise research. In 2017, this thesis – as one of three projects within the larger SNF project TraNQuIL – made use of the HERMES cohort study data to assess the effects of noise exposure on HERMES participants.

Using existing participant data of a study initially designed to assess a different question for a new research question has both advantages and disadvantages. The most compelling reason for using existing data is the cost effectiveness. This includes the reducing of time and efforts involved in the data collection process.

This 'second look' approach of using existing data post-hoc did also introduce some challenges. Even though documentation of the HERMES data collection process was meticulous, some information was not readily available.

A lot of the data preparation and analyses processes were well documented and helped the author of this thesis understand and learn about methodological work. But, writing code and data processing is a highly personal activity. Therefore the data folder systems, documentation and data treatment had a different handwriting for each of the three researchers. It therefore took some time to understand each system. In case more information was needed for clarification, the respective researcher and data collectors could be contacted. This approach usually allowed to clarify the situation, but required time, effort and a good memory of the respective researcher about their work up to 10 years ago.

I believe that using collected data beyond its primary scientific intention is a worthwhile endeavor and should be done as often as possible. This approach allows to more fully use existing data in order to generate additional valuable knowledge, and to further optimize the use of limited funds for scientific research.

7.5 Overall conclusion

The aim of this study was to fill knowledge gaps and further deepen what is known about the behavioural and cognitive effects of environmental noise on adolescents. Based on a robust study design and on the use of high-quality noise maps, and considering relevant behavioral information in personal exposure, the impact of a variety of confounders as well as other explanatory variables, and using multiple imputation, findings presented in this thesis showed slight but significant associations for peer problems and figural memory in cross-sectional analyses. Significant associations were found between exposure to road traffic noise at home and concentration constancy change within only one year. These associations over one year became even more visible, albeit no longer statistically significant due to the reduced power, when only considering participants whose bedrooms were adjacent to the noisiest street passing by the house. Seeing changes in cognitive function in association with noise exposure over only one year indicates a potentially strong relationship. It suggests that effects of noise may still continue to occur at later stages of development.

Environmental noise is an omnipresent threat to health for the majority of the population. Of environmental exposures, it is considered the second highest burden of disease after air pollution. Environmental noise does not appear as one of the global health problems targeted by the Sustainable Development Goals (SDG), though it relates to many (King, 2022). The findings presented in this dissertation provide additional evidence on the link between environmental noise exposure and both behavioural problems and cognitive function of adolescents and can be used in meta-analysis or the calculations of burden of disease. In turn, these can inform public health authorities, as well as health personnel and psychologists to mitigate noise-related risks for the public and for individuals.

References for Sections 1,2 and 7

Babisch, W. (2002). The noise/stress concept, risk assessment and research needs. *Noise and health, 4*(16), 1.

Babisch, W. (2014). Updated exposure-response relationship between road traffic noise and coronary heart diseases: a meta-analysis. *Noise and health, 16*(68), 1.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014, 10/30). Auditory and non-auditory effects of noise on health. *Lancet, 383*(9925), 1325-1332. https://doi.org/10.1016/S0140-6736(13)61613-X

Basner, M., & McGuire, S. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep. *International Journal of Environmental Research and Public Health, 15*(3), 519.

Bergström, K., Spilski, J., Mayerl, J., Möhler, U., Lachmann, T., & Klatte, M. (2015). Effects of aircraft noise on annoyance and quality of life in German children near Frankfurt/Main airport: results of the NORAH (noise-related annoyance, cognition, and health)-study. Proceedings of Euronoise,

Bilenko, N., Rossem, L. v., Brunekreef, B., Beelen, R., Eeftens, M., Hoek, G., Houthuijs, D., De Jongste, J. C., Kempen, E. v., & Koppelman, G. H. (2015). Traffic-related air pollution and noise and children's blood pressure: results from the PIAMA birth cohort study. *European journal of preventive cardiology, 22*(1), 4-12.

Brink, M., Schäffer, B., Vienneau, D., Foraster, M., Pieren, R., Eze, I., Cajochen, C., Probst-Hensch, N., Röösli, M., & Wunderli, J. (2019). A survey on exposure-response relationships for road, rail, and aircraft noise annoyance: Differences between continuous and intermittent noise. *Environment international, 125*, 277-290.

Brink, M., Schäffer, B., Vienneau, D., Pieren, R., Foraster, M., Eze, I. C., Rudzik, F., Thiesse, L., Cajochen, C., & Probst-Hensch, N. (2019). Self-reported sleep disturbance from road, rail and aircraft noise: exposure-response relationships and effect modifiers in the SiRENE study. *International Journal of Environmental Research and Public Health, 16*(21), 4186.

Clark, C., Crombie, R., Head, J., Van Kamp, I., Van Kempen, E., & Stansfeld, S. A. (2012). Does traffic-related air pollution explain associations of aircraft and road traffic noise exposure on children's health and cognition? A secondary analysis of the United Kingdom sample from the RANCH project. *American journal of epidemiology, 176*(4), 327-337.

Clark, C., Head, J., Haines, M., van Kamp, I., van Kempen, E., & Stansfeld, S. A. (2021). A meta-analysis of the association of aircraft noise at school on children's reading comprehension and psychological health for use in health impact assessment. *Journal of Environmental Psychology*, 101646.

Clark, C., Head, J., & Stansfeld, S. A. (2013). Longitudinal effects of aircraft noise exposure on children's health and cognition: a six-year follow-up of the UK RANCH cohort. *Journal of Environmental Psychology, 35*(2013), 1-9.

Clark, C., & Paunovic, K. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cognition. *International Journal of Environmental Research and Public Health, 15*(2), 285.

EEA. (2020). Environmental noise in Europe: 2020. *European Environmental Agency, 1*, 104.

Evans, G. W., & Lepore, S. J. (1993). Nonauditory effects of noise on children: A critical review. *Children's environments*, 31-51.

Evans, G. W., & Stecker, R. (2004). Motivational consequences of environmental stress. *Journal of Environmental Psychology, 24*(2), 143-165.

Fastl, H., Kuwano, S., & Namba, S. (1994). Psychoacoustics and rail bonus. Proc. inter-noise'94,

Goodman, R. (1997). The Strengths and Difficulties Questionnaire: a research note. *Journal of child psychology and psychiatry, 38*(5), 581-586.

Guski, R., Schreckenberg, D., & Schuemer, R. (2017). WHO environmental noise guidelines for the European region: a systematic review on environmental noise and annoyance. *International Journal of Environmental Research and Public Health, 14*(12), 1539.

Haines, M. M., Stansfeld, S. A., Brentnall, S., Head, J., Berry, B., Jiggins, M., & Hygge, S. (2001). The West London Schools Study: the effects of chronic aircraft noise exposure on child health. *Psychological Medicine, 31*(8), 1385.

Haines, M. M., Stansfeld, S. A., Job, R. S., Berglund, B., & Head, J. (2001). Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children. *Psychological Medicine, 31*(2), 265.

Hänninen, O., Knol, A. B., Jantunen, M., Lim, T.-A., Conrad, A., Rappolder, M., Carrer, P., Fanetti, A.-C., Kim, R., & Buekers, J. (2014). Environmental burden of disease in Europe: assessing nine risk factors in six countries. *Environmental health perspectives, 122*(5), 439.

Héritier, H., Vienneau, D., Foraster, M., Eze, I. C., Schaffner, E., Thiesse, L., Rudzik, F., Habermacher, M., Köpfli, M., & Pieren, R. (2017). Transportation noise exposure and cardiovascular mortality: a nationwide cohort study from Switzerland. *European journal of epidemiology, 32*(4), 307-315.

Hjortebjerg, D., Andersen, A. M. N., Christensen, J. S., Ketzel, M., Raaschou-Nielsen, O., Sunyer, J., Julvez, J., Forns, J., & Sørensen, M. (2016). Exposure to road traffic noise and behavioral problems in 7-year-old children: A cohort study. *Environmental health perspectives, 124*(2), 228.

Karipidis, I., Vienneau, D., Habermacher, M., Köpflii, M., Brink, M., Probst-Hensch, N., Röösli, M., & Wunderli, J.-M. (2014). Reconstruction of historical noise exposure data for environmental epidemiology in Switzerland within the SiRENE project. *Noise Mapping, 1*(2014), 3-14.

Kessler, R. C., Berglund, P., Demler, O., Jin, R., Merikangas, K. R., & Walters, E. E. (2005). Lifetime prevalence and age-of-onset distributions of DSM-IV disorders in the National Comorbidity Survey Replication. *Archives of general psychiatry, 62*(6), 593-602.

King, E. A. (2022, 2022/05/04). Here, There, and Everywhere: How the SDGs Must Include Noise Pollution in Their Development Challenges. *Environment: Science and Policy for Sustainable Development, 64*(3), 17-32. https://doi.org/10.1080/00139157.2022.2046456

Klatte, M., Bergström, K., & Lachmann, T. (2013). Does noise affect learning? A short review on noise effects on cognitive performance in children. *Frontiers in psychology, 4*, 578.

Klatte, M., Spilski, J., Mayerl, J., Möhler, U., Lachmann, T., & Bergström, K. (2017). Effects of aircraft noise on reading and quality of life in primary school children in Germany: results from the NORAH study. *Environment and Behavior, 49*(4), 390-424.

Kristiansen, J., Persson, R., Lund, S. P., Shibuya, H., & Nielsen, P. M. (2013). Effects of classroom acoustics and self-reported noise exposure on teachers' well-being. *Environment and Behavior, 45*(2), 283-300.

Lim, J., Kweon, K., Kim, H.-W., Cho, S. W., Park, J., & Sim, C. S. (2018). Negative impact of noise and noise sensitivity on mental health in childhood. *Noise Health, 20*(96), 199.

Locher, B., Piquerez, A., Habermacher, M., Ragettli, M., Röösli, M., Brink, M., Cajochen, C., Vienneau, D., Foraster, M., & Müller, U. (2018). Differences between outdoor and indoor sound levels for open, tilted, and closed windows. *International Journal of Environmental Research and Public Health, 15*(1), 149.

Möhler, U. (1988). Community response to railway noise: a review of social surveys. *Journal of Sound and Vibration, 120*(2), 321-332.

Münzel, T., Gori, T., Babisch, W., & Basner, M. (2014). Cardiovascular effects of environmental noise exposure. *European heart journal, 35*(13), 829-836.

Münzel, T., Sørensen, M., & Daiber, A. (2021). Transportation noise pollution and cardiovascular disease. *Nature Reviews Cardiology, 18*(9), 619-636. https://doi.org/10.1038/s41569-021-00532-5

Papanikolaou, M., Skenteris, N., & Piperakis, S. (2015). Effect of external classroom noise on schoolchildren's reading and mathematics performance: correlation of noise levels and gender. *International journal of adolescent medicine and health, 27*(1), 25-29.

Saucy, A., de Hoogh, K., Vienneau, D., Tangermann, L., Schäffer, B., Wunderli, J.-M., Probst-Hensch, N., & Röösli, M. (2021). Mutual effects of fine particulate matter, nitrogen dioxide, and fireworks on cause-specific acute cardiovascular mortality: a case-crossover study in communities affected by aircraft noise. *Environmental pollution, 291*, 118066.

Saucy, A., Ragettli, M. S., Vienneau, D., de Hoogh, K., Tangermann, L., Schäffer, B., Wunderli, J.-M., Probst-Hensch, N., & Röösli, M. (2021). The role of extreme temperature in cause-specific acute cardiovascular mortality in Switzerland: a case-crossover study. *Science of the Total Environment, 790*, 147958.

Saucy, A., Schäffer, B., Tangermann, L., Vienneau, D., Wunderli, J.-M., & Röösli, M. (2020). Individual aircraft noise exposure assessment for a case-crossover study in Switzerland. *International Journal of Environmental Research and Public Health, 17*(9), 3011.

Saucy, A., Schäffer, B., Tangermann, L., Vienneau, D., Wunderli, J.-M., & Röösli, M. (2021). Does night-time aircraft noise trigger mortality? A case-crossover study on 24 886 cardiovascular deaths. *European heart journal, 42*(8), 835-843.

Saucy, A., Schffer, B., Tangermann, L., Vienneau, D., Wunderli, J.-M., & Röösli, M. (2019). Aircraft noise exposure assessment for a case-crossover study in Switzerland. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings, 259*(6), 3299-3308.

Schubert, M., Hegewald, J., Freiberg, A., Starke, K. R., Augustin, F., Riedel-Heller, S. G., Zeeb, H., & Seidler, A. (2019). Behavioral and emotional disorders and transportation noise among children and adolescents: a systematic review and meta-analysis. *Journal International Journal of Environmental Research Public Health*

16(18), 3336.

Seligman, M. E. (1972). Learned helplessness. *Annual review of medicine, 23*(1), 407-412.

Shield, B., Conetta, R., Dockrell, J., Connolly, D., Cox, T., & Mydlarz, C. (2015). A survey of acoustic conditions and noise levels in secondary school classrooms in England. *The Journal of the Acoustical Society of America, 137*(1), 177-188.

Śliwińska-Kowalska, M., & Zaborowski, K. (2017). WHO environmental noise guidelines for the European region: a systematic review on environmental noise and permanent hearing loss and tinnitus. *International Journal of Environmental Research and Public Health, 14*(10), 1139.

Stansfeld, S., Hygge, S., Clark, C., & Alfred, T. (2010). Night time aircraft noise exposure and children's cognitive performance. *Noise and health, 12*(49), 255.

Sterne, J. A., White, I. R., Carlin, J. B., Spratt, M., Royston, P., Kenward, M. G., Wood, A. M., & Carpenter, J. R. (2009a). Multiple imputation for missing data in epidemiological and clinical research: potential and pitfalls. *BMJ, 338*.

Sterne, J. A., White, I. R., Carlin, J. B., Spratt, M., Royston, P., Kenward, M. G., Wood, A. M., & Carpenter, J. R. (2009b). Multiple imputation for missing data in epidemiological and clinical research: potential and pitfalls. *BMJ, 338*(338).

Thompson, R., Smith, R. B., Karim, Y. B., Shen, C., Drummond, K., Teng, C., & Toledano, M. B. (2022). Noise pollution and human cognition: an updated systematic review and meta-analysis of recent evidence. *Environment international, 158*, 106905.

Tiesler, C. M., Birk, M., Thiering, E., Kohlböck, G., Koletzko, S., Bauer, C.-P., Berdel, D., von Berg, A., Babisch, W., & Heinrich, J. (2013). Exposure to road traffic noise and children's behavioural problems and sleep disturbance: results from the GINIplus and LISAplus studies. *Environmental research, 123*(13), 1-8.

van Kempen, E., Casas, M., Pershagen, G., & Foraster, M. (2018). WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cardiovascular and metabolic effects: a summary. *International Journal of Environmental Research and Public Health, 15*(2), 379.

Van Kempen, E., Van Kamp, I., Lebret, E., Lammers, J., Emmen, H., & Stansfeld, S. (2010). Neurobehavioral effects of transportation noise in primary schoolchildren: a cross-sectional study. *Environmental Health, 9*(1), 1-13.

van Kempen, E. E., Van Kamp, I., Stellato, R. K., Lopez-Barrio, I., Haines, M. M., Nilsson, M. E., Clark, C., Houthuijs, D., Brunekreef, B., & Berglund, B. (2009). Children's annoyance reactions to aircraft and road traffic noise. *The Journal of the Acoustical Society of America, 125*(2), 895-904.

Vienneau, D., Héritier, H., Foraster, M., Eze, I. C., Schaffner, E., Thiesse, L., Rudzik, F., Habermacher, M., Köpfli, M., & Pieren, R. (2019). Façades, floors and maps–Influence of exposure measurement error on the association between transportation noise and myocardial infarction. *Environment international, 123*(2019), 399-406.

Vienneau, D., Saucy, A., Schäffer, B., Flückiger, B., Tangermann, L., Stafoggia, M., Wunderli, J. M., & Röösli, M. (2022). Transportation noise exposure and cardiovascular mortality: 15-years of follow-up in a nationwide prospective cohort in Switzerland. *Environment international, 158*, 106974. https://www.sciencedirect.com/science/article/pii/S0160412021005997

Weyde, K. V., Krog, N. H., Oftedal, B., Magnus, P., Øverland, S., Stansfeld, S., Nieuwenhuijsen, M. J., Vrijheid, M., de Castro Pascual, M., & Aasvang, G. M. (2017). Road traffic noise and children's inattention. *Environmental Health, 16*(1), 127.

WHO. (2009). Night noise guidelines for Europe. *WHO Regional Office Europe*. http://www.euro.who.int/__data/assets/pdf_file/0017/43316/E92845.pdf

WHO. (2011). *Burden of disease from environmental noise: quantification of healthy life years lost in Europe*. World Health Organization. Regional Office for Europe.

WHO. (2018). Environmental Noise Guidelines for the European Region (2018).

Wunderli, J. M., Pieren, R., Habermacher, M., Vienneau, D., Cajochen, C., Probst-Hensch, N., Röösli, M., & Brink, M. (2016). Intermittency ratio: a metric reflecting short-term temporal variations of transportation noise exposure. *Journal of Exposure Science and Environmental Epidemiology, 26*(6), 575-585.

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2017 - current	**PhD candidate, Swiss Tropical and Public Health Institute (Swiss TPH),** *The effects of transportation noise on cognitive functions and behaviour in adolescents*
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Work experience (in order of relevance):

Duration	8 months (2015)
Position	First 6 months intern, then project team member
Key responsibilities	Assisting in and running health campaigns Working in multidisciplinary groups (public health specialists, scientific researchers, marketing specialists, software developer etc.) Developing a smartphone application Writing reports

Company	Federal Office of Public Health FOPH (Bundesamt für Gesundheit BAG)
Country	Switzerland

Duration	3 months (2010)
Position	Intern
Key responsibilities	Reviewing and drafting of background and introduction of the Cambodia Survey on Iodine Nutrition. Data analysis of the Cambodia Survey on Iodine Nutrition using SPSS. Survey design, data collection, analysis and write-up of a small study to assess the appropriateness of a Cambodia Millennium Goal target on iodized salt. Creation of and using a tool for carrying out maternal death near miss analyses.
Company	UNICEF
Country	Cambodia
Duration	7 months (2016)
Position	Junior Consultant
Key responsibilities	Co-managing a nationwide event on biodiversity (“Festival der Natur”), using mass media and PR-strategies Developing the events´ website Administrative tasks
Company	Von salis communication
Country	Switzerland

Duration	6 months (2014)
Position	Intern
Key responsibilities	Conducting a qualitative study on the diffusion of the health program. Creating the questions for the master thesis and conducting data collection and analysis. Optimizing organizational structures of the institute.
Company	YoBEKA – a health intervention in schools.
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Relevant trainings, workshops, seminars and publications:

May 2022	Paper under review at Environmental Research: The association of road traffic noise with cognition in adolescents: A cohort study in Switzerland
Jan. 2022	Publication: The association of road traffic noise with problem behaviour in adolescents: A cohort study
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June 2021	ICBEN Congress, oral presentation
Feb. 2021	ISEE Young 2021, oral presentation
Oct. 2018	Publication: Wie wirkt Lärm auf Kinder?, Paediatrica Col. 29-4
Aug. 2018	ISES-ISEE 2018 Joint Annual Meeting – poster and oral presentation
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