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Association of transportation noise with sleep during the first year of life: A longitudinal study

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ABSTRACT

Study objectives: During infancy, adequate sleep is crucial for physical and neurocognitive development. In adults and children, night-time noise exposure is associated with sleep disturbances. However, whether and to what extent infants' sleep is affected, is unknown. Thus, this study investigated the relationship between nocturnal transportation noise and actimetry-derived habitual sleep behavior across the first year of life.
Methods: In 144 healthy infants (63 girls), nocturnal (23:00–7:00) transportation noise (i.e., road, railway, and aircraft) was modelled at the infants' individual places of residence. Using actimetry, we recorded movement patterns for 11 days in a longitudinal design at 3, 6, and 12 months of age and derived the recently proposed core sleep composites of night-time sleep duration, activity, and variability. Using linear mixed-effects models, we determined associations between noise exposure and sleep composites. Sex, gestational age, parents' highest educational level, infants' age, and the existence of siblings served as control variables.
Results: In models without interactions, night-time transportation noise was unrelated to sleep composites across the first year of life ($p > .16$). Exploratory analyses of an interaction between noise and the existence of siblings yielded an association between night-time transportation noise and sleep duration in infants without siblings only ($p = .004$).
Conclusion: In our study, sleep in infants during the first year of life was relatively robust against external perturbation by night-time transportation noise. However, particularly in children without siblings increasing night-time transportation noise reduced sleep duration. This suggests that the habitual noise environment may modulate individual susceptibility to adverse effects of noise on sleep.

1. Introduction

Epidemiological research has repeatedly demonstrated an association between transportation noise exposure and adverse effects on various health aspects, including cardiovascular diseases (Cai et al., 2018), and metabolic syndrome (Christensen et al., 2016), as well as cognitive functions and behavioral problems (Tiesler et al., 2013; Stansfeld and Clark, 2015) in adults. In children, an association of noise exposure with cardiac and metabolic diseases has likewise been reported (Stansfeld and Clark, 2015). Although the precise mechanisms remain to be identified, sleep has repeatedly been ascribed a seminal mediating role in the effects of transportation noise on the aforementioned health

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outcomes. Specifically, a large body of literature supports the role of reduced sleep duration (Muzet, 2007), self-reported quality (Griefahn and Muzet, 1978; Marks and Griefahn, 2007), changes in sleep architecture with decreased proportions of deep sleep (Wilkinson and Campbell, 1984), and increased sleep fragmentation (Griefahn and Muzet, 1978), for a review see Pirrera et al., 2010. In children, exposure to road traffic noise has been associated with reduced self-reported sleep quality (Tiesler et al., 2013; Ising and Ising, 2002; Öhrström et al., 2006), increased daytime sleepiness (Öhrström et al., 2006), reduced parent-reported sleep duration and sleep problems in girls (Weyde et al., 2017), and problems with hyperactivity or inattention (Tiesler et al., 2013). Although effects are plausible, the potential effects of noise from other sources such as siblings have hardly received any attention. Sufficient and good sleep is essential for younger children since chronic sleep problems in children have been linked to poor long-term outcomes regarding neuro-cognitive development (Maski and Kothare, 2013) and metabolic health (Reiter et al., 2012).

In children, most previous studies used questionnaires to assess sleep quality and duration (Tiesler et al., 2013; Ising and Ising, 2002), and it is largely unknown whether associations assessed via questionnaires hold true if sleep is measured objectively. To the best of our knowledge, only three studies in children evaluated the association between environmental noise exposure and actimetry-assessed sleep using a cross-sectional design (Öhrström et al., 2006; Weyde et al., 2017; Bagley et al., 2015). Öhrström et al. (2006) assessed sleep outcomes in parents and their children (9–12 years old) via questionnaires. In a subset of the sample, they additionally used sleep logs and objective actimetry recordings for a four-day period. Although the authors report an association between higher noise exposure and subjective sleep quality (self-reported ranking from one to 10), no association between noise and sleep was found with objective sleep parameters (e.g., latency, activity, duration) derived from actimetry. This discrepancy suggests that associations between noise exposure and sleep parameters may depend on the measurement modality. Generally, studies using self-report data seem to yield more consistent results than those relying on objective measurements (Pirrera et al., 2010).

A possible reason for the scarcity of studies using objective sleep measures in children is the methodological challenges researchers face. More precisely, a reliable assessment of sleep in younger children and infants in their home environment across several nights and days can only be achieved with actimetry. However, this way of assessing sleep is challenging, particularly because of the many degrees of freedom a researcher has at various data handling steps. Unfortunately, this also often hinders replicability and comparability of results (Schoch et al., 2019). Moreover, some of the frequently used parameters are difficult to compare across age groups (Schoch et al., 2020). To circumvent these issues, we made use of an approach recently proposed by Schoch and colleagues (Schoch et al., 2019). This approach entails further computational steps (Schoch et al., 2020) to derive three sleep composites, namely nocturnal sleep *duration*, sleep *variability* across nights, and *activity* during the sleep episode. The three sleep composites were each calculated at three different time points during the first year of life (i.e., 3, 6, and 12 months of age) for 144 children in Switzerland. We then investigated the associations between nocturnal transportation noise (i.e., road, railway, aircraft noise, and a combined noise measure) and each sleep composite. We expected increased night-time (23:00-7:00) traffic noise exposure to be associated with shorter sleep duration and higher activity levels during sleep but not variability of sleep patterns across days. Analyses were carefully controlled for factors previously reported to be associated with infant sleep, that is parental education level (McDowall et al., 2017), age (Paavonen et al., 2020; Jenni et al., 2004), gestational age (Watt and Strongman, 1985), and sex (Franco et al., 2020). Additionally, we explored the association between the habitual noise environment and effects of transportation noise. Here, the presence of siblings was considered a central factor shaping the habitual noise environment (Tiesler et al., 2013).

2. Methods and materials

2.1. Participants

Actimetry data were acquired in a total of 144 term-born healthy infants (63 girls; 39.9 $\pm$ 1.1 weeks gestation) with a birth weight of at least 2500 g in a longitudinal fashion at age 3 months (T1; 2.8 $\pm$ 0.2 months), 6 months (T2; 5.7 $\pm$ 0.2 months), and 12 months (T3; 11.8 $\pm$ 0.2 months). Infants had to be in a good general state of health, be primarily breastfed at the age of three months (i.e., at least 50 % of daily food intake through breastfeeding), and born by vaginal delivery (i.e., no caesarean section). Parents noted their infant's illnesses in a diary and either skipped the recording on days when the baby was unwell, or these days were later excluded from the analyses. Seven families moved between the first and the second assessment, and eleven families moved between the second and third assessment, thus experiencing a potential change in transportation noise exposure. Diseases or lesions of the central nervous system, acute or chronic medical conditions, psychological trauma since birth, and a positive family anamnesis regarding narcolepsy, psychotic, or bipolar disorder, served as exclusion criteria. Additionally, traveling across time zones with >1-h time difference in the four weeks prior to each assessment, intake of medication that could alter the sleep-wake cycle, and antibiotics prescribed before the first assessment at the age of three months led to exclusion from the study. Families were recruited via maternity wards, paediatricians, midwives, day-cares, letters, social media and personal contacts. Additionally, flyers were distributed at universities, libraries, supermarkets, schools, family organizations, and community centres. Parents had to have sufficient command of German, as study forms and instructions were in German. Written parental consent was obtained before study enrolment. Regarding the sleep situation, at T1 123 infants slept in the parents' room, 20 alone and one infant shared a room with another person. At T2, 105 still slept in the parents' room, 33 alone, and 6 shared the room. At the age of 12 months (T3), 62 and 61 infants slept in their parents' room or alone, respectively, and 21 shared a room. The dataset has been included in a previous publication with a different focus (Schoch et al., 2020), a subset of 50 participants has also been used in Schoch et al., 2019. Ethical approval was provided by the cantonal ethics commission (Ethikkommission Zürich; 2016-00730). The study was conducted in accordance with Swiss law and the Declaration of Helsinki.

2.2. Actimetry data collection

At each of the three time points, we aimed to collect ankle actimetry using accelerometers for 11 continuous days using GENEactiv accelerometers (Activinsights Ltd., Kimbolton, UK; 43 $\times$ 40 $\times$ 13 mm, Micro-Electro-Mechanical Systems sensor, 16 g, 30 Hz frequency; sensitive for $\pm$8 g range at 3.9 mg resolution). Actimeters were attached to the infants' left ankles using a sock with a small pocket or a Tyvek paper strap, and parents were instructed not to remove it except when the infant's feet were under water, e.g., during bathing. Parents were instructed to attach the actimeter on the first day before habitual bedtime and remove it after waking up on the last day of data collection. However, in some cases, it was not possible to record data for the full 11 days, or it was extended beyond 11 days (for details, see Schoch et al., 2020). For their participation, families received small gifts for the infant.

2.3. Actimetry data reduction

Actimetry data were first extracted from the actimetry devices (GENEactiv PC Software, version 3.1) and imported into Matlab (Mathworks, Natick, USA; R2016b). Following conversion to activity counts, data were pre-processed by applying a bandpass filter (3–11 Hz) and compressing signals to 15-s bins. Data from all three coordinate axes were integrated and compressed to one value per minute bins using the sum of square. Subsequently, sleep and wake periods were identified using a recently published modification (Schoch et al., 2019) of the algorithm by Sadeh et al., 1995. This algorithm calculates the probability for sleep and wake for each minute and assigns the state with the higher probability to each period. The advantages of this novel 6-step modification have been evaluated in detail in Schoch et al., 2019. Specifically, it improves agreement with a paper-pencil 24-h diary, in which parents reported on sleep and wakefulness or external/passive movement in detail by means of 15-min periods, and improves agreement among commonly used algorithms for analysing infant actimetry (Oakley/Respironics). Specific modifications include (i) setting individual thresholds to distinguish wake from sleep for each infant, (ii) adjusting against the bias of the algorithm to overemphasise sleep, (iii) rescoring of actimeter non-wear periods, (iv) rescoring according to Webster et al., 1982, (v) implementing information from the 24-h diary for movements during daytime sleep, and (vi) smoothing of the data in the presence of short wake periods during the night. Subsequently, 48 sleep and sleep variability variables of interest were calculated (e.g., bedtime, variability of bedtime, getting up time, variability of getting up time, sleep latency, etc.). The sleep composites were then derived from these infant sleep variables using principal component analysis (PCA). After excluding sleep variables with absolute factor loadings falling below 0.512 and excluding one other variable due to interpretability issues, 33 variables were included in the final PCA solutions with 3–10 single sleep variables being assigned to each sleep composite. Using R version 3.5.0 (R Core Team, 2015), missing and excluded data (0 %–22.32 % per variable) were imputed using the packages 'mice' (van Buuren and Groothuis-Oudshoorn, 2011) and 'miceadds' (Robitzsch and Grund, 2020), 'MKmisc' (Kohl et al., 2019) and 'micemd' (Audigier and Resche-Rigon, 2019). The method '2l.pmm' was used for numerical variables, using the participant ID as the grouping variable and assessment age (3/6/12 months) as slope. 'Logreg' was used for binary variables and categorical variables were predicted using either 'polyreg' or 'polyr'. A two-level structure was not included in binary and categorical variable prediction. A total of 100 imputations were run with 100 iterations each. Visual checks for data quality of imputations were performed (observed vs. imputed values and convergence of iterations).

Following an approach recently proposed (Staples et al., 2019) and implemented in a large infant cohort (Schoch et al., 2020), we reduced the actimetry data to three "sleep composites" reflecting key dimensions of infant sleep behavior: *sleep duration*, reflecting the quantity of sleep during the night; *sleep variability*, reflecting differences in sleep timing and duration from day to day; and *sleep activity*, which reflects movements and awakenings during the night. This approach circumvents the problem of selecting some sleep variables from a range of potential ones thereby increasing reproducibility. Additionally, the composites are comparable across age groups, which is particularly advantageous in longitudinal designs involving infants, where sleep changes markedly during the first months of life (Schoch et al., 2020).

2.4. Transportation noise exposure

The procedures for the estimation of transportation noise exposure have been described in more detail elsewhere (Karipidis et al., 2014; Schlatter et al., 2017). In brief, annual means of equivalent continuous sound pressure levels (LAeq) were modelled for the geographical coordinates of each participant's place of residence. Noise exposure was modelled at the most exposed façade for each of the three noise sources: road, railway, and aircraft noise (major airports in Switzerland: Basel, Geneva, Payerne, Zurich). To this end, we used a physical propagation model taking into account the emission sources, the three-dimensional building structure, and the physical law of sound propagation. More specifically, road noise modelling was accomplished with the sonROAD emission model (Heutschi, 2004) and the StL-86 sound propagation model (Federal office for the Environment FOEN, 1995). Aircraft noise was modelled using the FLULA2 model (Swiss Federal Laboratories for Materials Science and Technology (EMPA), 2010) and railway noise was calculated with the sonRAIL emission model (Thron and Hecht, 2010) and the SEMI-BEL sound propagation model (Federal Office for the Environment (FOEN), 2009). Additionally, a value for the combined noise exposure from all three sources was computed. In this publication, we focus on the combined noise during the night, that is, between 23:00 and 7:00. The noise model was based on measures from the year 2011.

Following Heritier (Héritier et al., 2017), LAeq values were censored at 30 dB for aircraft and railway and at 35 dB for road and combined noise, i.e., values below this threshold were set to this lowest value (cf. Suppl. Table 1 for the number of censored values at each time point). These levels were prior-selected on the basis of being physiologically meaningful, i.e., audible inside a building and to account for background noise in the low exposure range. No noise estimates could be computed for one participant with place of residence outside Switzerland, which resulted in exclusion. For two additional participants, noise exposure information was missing at one respective time point due to missing address information. However linear mixed models can handle this type of missing information, and the available data were included in the analyses.

2.5. Covariates

In the adjusted models, covariates that have previously been shown or assumed to impact on infant sleep were included. This included gestational age, sex, the child's exact age, whether there were older children in the household (43.1 % had at least one sibling), and the parents' educational background (highest education of both; 9 % apprenticeship, 0.7 % higher secondary education, 68.1 % university degree, 22.2 % PhD).

2.6. Statistical analyses

All statistical analyses were done in R (R Core Team, 2015) version 4.0.2. Linear mixed models were calculated using the 'lme4' package (Bates et al., 2015) following the analytic pipeline described in van Buuren, 2018. Gestational age, sex (male, female), exact age, whether there were siblings (binary; yes/no), as well as the noise estimate were included as fixed effects, whereas the participant ID was modelled as a random intercept. Separate models were calculated for each sleep composite (i.e., sleep activity, sleep variability, and sleep duration) and each noise variable (i.e., road, railway, aircraft, and combined noise exposure). In Wilkinson–Rogers notation (Wilkinson and Rogers, 1973), the models take the following form (for mathematical notation please see the supplemental material):

$$\text{SleepVariable} \sim (1|\text{ParticipantID}) + \text{education} + \text{gestation\_age} + \text{sex} + \text{exact\_age} + \text{siblings\_binary} + (or \times)\ \text{noise\_estimate}$$

Each model was calculated twice, once without any interactions between fixed effects (primary model) and once with noise estimates being allowed to interact with the existence of siblings (exploratory) in order to account for the habitual noise environment. The interaction was included to explore whether children with siblings, who differ regarding the habitual noise environment from children without, respond differently to nocturnal traffic noise.

The significance level was $p = .05$ (two-sided). Effects with $p < .1$ are denoted trends. The interpretation of the results is based on the *general pattern* and *not* single results as recommended by Wasserstein, Schirm, Lazar (Wasserstein et al., 2019), wherefore the interpretation may also take into account trends. For fixed effects, we report *t*-values along with degrees of freedom (*df*) rounded to the next integer. We also report 95 % confidence intervals for fixed effects.

Potential differences in noise exposure between the noise sources (i.e., aircraft, railway, road, and combined) across the three time points of assessment (i.e., age 3, 6, and 12 months) were investigated with an analysis of variance (ANOVA) using the 'ez' package for R (Lawrence, 2013). Where the assumption of sphericity was violated, we applied Greenhouse–Geisser corrections and reported the corresponding epsilon value along with F and p values. Additionally, we report the generalized eta square (η_{ge}) as a measure of the effect size for ANOVAs. Significant effects in the ANOVA were followed up with Welch two-sample t-tests. We also report Pearson correlations for the relationship between individual noise sources and combined noise. The p-values obtained in follow-up t-tests as well as in correlation analyses were corrected for multiple comparisons using the approach suggested by Benjamini and Hochberg (1995). For the follow-up t-tests we report Cohen's d as a measure of the effect size.

3. Results

3.1. Noise

Mean noise levels were in the range of expected nocturnal noise levels (Héritier et al., 2017). Noise levels differed between the three noise sources (i.e., road, railway, aircraft; $F(3,1260) = 756.62$, $p < .001$, $\eta_{ge} = 0.51$, cf. Table 1). Estimates for road traffic (47.9 dB $\pm$ 7.7) were higher than for aircraft (32.7 dB $\pm$ 5.2; aircraft vs. road: $t(740) = -33.73$, $p < .001$, $d = 2.32$) or railway lines (34.9 dB $\pm$ 8.8; railway vs. road: $t(828) = 23.07$, $p < .001$, $d = 1.59$). Additionally, noise estimates due to aircraft were lower than estimates for road noise ($t(740) = -33.73$, $p < .001$, $d = 2.32$). Generally, road ($r = 0.87$, $p < .001$) and railway ($r = 0.38$, $p < .001$), but not aircraft ($r = 0.06$, $p = .23$) noise estimates were correlated with the combined noise estimate reflecting respective contributions. Noise levels for each source as well as combined noise estimates did not differ between the three assessment points at 3, 6, and 12 months of age ($F(2,420) = 0.11$, $p = .9$, $\eta_{ge} < 0.001$), neither was there an interaction between the noise source and time of assessment ($F(6,1260) = 0.11$, $p = 1.0$, $\eta_{ge} < 0.001$).

3.2. Sleep and combined noise

3.2.1. Sleep duration

Here, we tested whether nocturnal sleep duration is modulated by nocturnal traffic noise exposure. We found that the existence of siblings and, by trend, higher noise exposure, predicted shorter sleep duration (siblings: $t(405) = -2.45$, $p = .003$; noise: $t(401) = -1.93$, $p = .054$), but only if the interaction term siblings $\times$ noise was included. Additionally, in infants with siblings, increasing noise levels did not seem to have a negative effect on nocturnal sleep duration ($t(406) = 2.82$, $p = .005$; cf. Fig. 1 for an illustration). Generally, longer nocturnal sleep was predicted by older age ($t(373) = 3.63$, $p < .001$, with siblings $\times$ noise interaction: $t(373) = 3.61$, $p < .001$) and, by trend, by an older gestational age ($t(403) = 1.88$, $p = .061$, with interaction: $t(401) = 1.91$, $p = .057$). Table 2 provides an overview of the results, for the results for individual noise sources please see Suppl. Tables 2-4.

3.2.2. Sleep activity

Sleep activity describes the amount and extent of movements as well as the fragmentation of sleep. In contrast to our hypothesis, sleep activity was not modulated by night-time noise ($ps > .16$). Generally, lower sleep activity was associated with female sex ($t(404) = -3.54$, $p < .001$; with siblings $\times$ noise IA: $t(404) = -3.53$, $p < .001$), and an older age at the time of assessment ($t(392) = -15.83$, $p < .001$; with IA: $t(391) = -15.83$, $p < .001$). Additionally, when the highest educational background of the parents was a university degree or PhD compared to an apprenticeship, sleep activity was reduced (university degree: $t(399) = -2.01$, $p = .045$; with IA: $t(398) = -2.00$, $p = .047$; PhD: $t(403) = -1.88$, $p = .061$; with IA: $t(402) = -1.87$, $p = .063$). When the interaction term was not included, the existence of siblings additionally predicted reduced sleep activity ($t(404) = -2.16$, $p = .031$). For an overview of the results, see Table 2; for the results for individual noise sources please see Suppl. Tables 2–4.

3.2.3. Sleep variability

Sleep variability describes the consistency and regularity of sleep patterns across days. In line with our hypothesis, sleep variability did not vary with noise exposure ($ps > .43$). Generally, lower variability was predicted by an older age at the time of assessment ($t(385) = -6.88$, $p < .001$; with siblings $\times$ noise IA: $t(384) = -6.88$, $p < .001$). When the interaction term was not included in the model, the existence of siblings ($t(401) = -2.49$, $p < .013$) as well as higher parental education—that is, at least one of the parents holds a PhD compared to an apprenticeship—was related to increased regularity of sleep patterns ($t(399) = -1.90$, $p = .058$; with IA: $t(398) = -1.86$, $p = .063$). For an overview of the results, see Table 2; for the results for individual noise sources, please see Suppl. Tables 2–4.

Table 1
Overview of noise exposure levels [equivalent continuous sound pressure level, LAeq N in dB] for each noise source between 23:00 and 7:00.

Noise source	Mean	SD	Min	Max	Median
LAeq N aircraft noise exposure (dB)	32.7	5.2	30	57.2	30
LAeq N rail noise exposure (dB)	34.7	8.8	30	72.6	30
LAeq N road noise exposure (dB)	48.0	7.7	35	65.4	47.2
LAeq N combined noise exposure (dB)	49.8	7.6	35	72.6	49

LAeq N: Nocturnal equivalent continuous sound level. Note that minimal values reflect the values at which noise estimates were censored.

4. Discussion

In this study, we investigated whether night-time transportation noise exposure is related to healthy infants' objectively assessed sleep quality during their first year of life. Primary analyses using the main model did not confirm the hypothesized associations between transportation noise and infant sleep composites (i.e., nocturnal sleep duration, variability of sleep across days, and activity during the night). This suggests a relative robustness of infant sleep against external perturbation possibly underlining its developmental importance. However, an infant's habitual noise environment may modulate the relationship between noise and sleep. Thus, we further explored the effects of an interaction between the existence of siblings and transportation noise. Particularly in children without siblings, higher night-time noise exposure was linked to decreased night-time sleep duration. The size of this effect was comparable to the developmental changes in nocturnal sleep duration from three to twelve months of age. Sleep variability across days, as well as physical activity and awakenings during sleep remained unaffected by transportation noise.

In more detail, we found that infant night-time sleep during the first year of life was relatively robust against effects of transportation noise. This is well in line with the ontogenetic importance of sleep for adequate and healthy development (Maski and Kothare, 2013; Reiter et al., 2012). Beyond this robustness, our findings tentatively suggest that infants exposed to less in-house noise, particularly from siblings, may be more sensitive to noise at night and thus more susceptible to the adverse effects of transportation noise. Interestingly, Tiesler et al. (2013) similarly reported a stronger association between night-time noise and self-reported sleeping problems in children aged 10 years, who slept alone in a room. Although differences in the participants' age and the sleep assessment methodology limit the comparability, the findings are well in-line with the results of the present study. Together, they provide support for the notion that the habitual noise environment may modulate the effect of transportation noise on sleep. Although a study in 80 school-age children found no association between objective sleep duration and noise (Öhrström et al., 2006), Weyde et al., 2017 reported that in a large sample of 2665 school-aged children in Norway noise exposure was indeed linked to reduced self-reported sleep duration, however only in girls. In our infant sample, an effect of sex was not

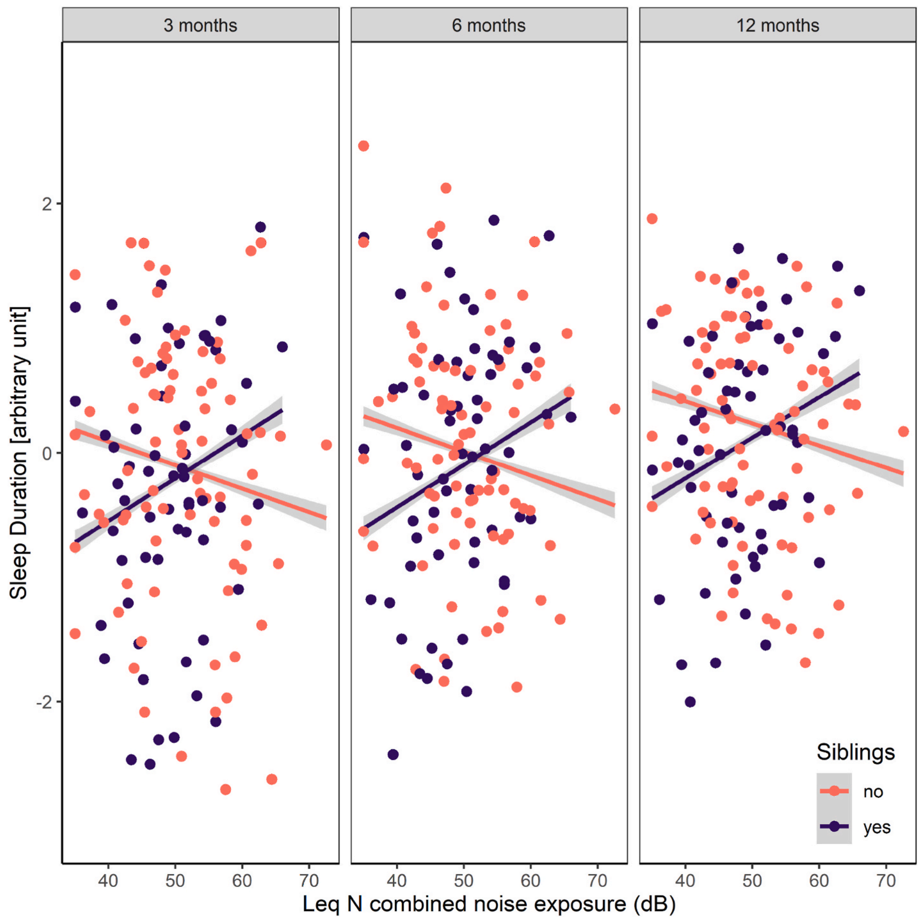

Fig. 1. Longitudinally, objectively assessed sleep during the first year of life seems robust against night-time transportation noise exposure. However, infants in a sleep-protective environment (e.g., without siblings) may be at increased risk for adverse effects of transportation noise on sleep.

evident regarding sleep duration, it only played a role regarding the extent of physical activity and awakenings during the night, where girls had quieter sleep. Although methodological differences preclude a direct comparison between the previous (Weyde et al., 2017) and our study, our results underline the relevance of sex for infant sleep as early as during the first months of life.

Beyond sleep duration, no further associations between night-time noise exposure and the other sleep composites, that is, sleep variability across days or physical activity during sleep, were evident in the present study. However, we observed that the control variable parental education was associated with infants' physical activity during sleep. More specifically, infants of parents with a university degree or PhD presented with reduced sleep activity, compared to infants whose parents had a lower educational level. Indeed, education has previously been reported to be associated with infants' sleep (McDowall et al., 2017). Parents with higher educational levels reported earlier bed and wake times and more consistent sleep routines, as well as less sleep problems and higher sleep quality. Our outcome parameter sleep activity and the sleep characteristics assessed by McDowall et al. (2017) clearly reflect different sleep properties, but together they confirm that parental education impacts on the infants' sleep.

Although we had generally expected increased fragmentation or activity levels but not variability at higher noise levels, comparisons with previous studies are again limited by the assessment modality (i.e., actimetry vs. subjective reports). Differences in participant age may likewise well have played a role in this context because circadian sleep-wake patterns and overall sleep duration undergo major changes during the first years of life. In particular, a diurnal sleep-wake pattern develops during the first months after birth: sleep becomes increasingly consolidated at night and less fragmented, and overall sleep need decreases continuously until adolescence (Paavonen et al., 2020). At the same time, active or rapid-eye movement sleep proportions decrease during the first nine months after birth while quiet or non-rapid eye movement sleep proportions increase (Jenni et al., 2004). These changes may well modulate susceptibility to noise effects.

One mechanism by which effects of noise on sleep duration could be mediated is the so-called cortisol awakening response that follows the end of sleep in the morning. In toddlers between 12 and 24 months of age, higher waking cortisol levels have been associated with shorter total nocturnal sleep time and earlier awakening (Bright et al., 2014). Furthermore, studies suggest that higher waking cortisol levels reflect higher stress levels in children (DeCaro and Worthman, 2008), just as in adults (Dahlgren et al., 2009; Fries et al., 2009). As daily noise exposure has been shown to be associated with elevated cortisol levels in children (Evans et al., 2001), this may depict one mechanism by which transportation noise also shortens nocturnal sleep in infants. Critically, several studies suggest that sleep duration is especially essential for healthy physical and cognitive (for a review see Tham et al., 2017; Gertner et al., 2002) as well as mental (Spruyt et al., 2008) development of infants. Although these developmental aspects have not been studied here, we speculate that our and others' findings may suggest that nocturnal noise exposure could adversely impact infant development.

The study's strengths include the longitudinal and well-controlled data collection with the acquisition of objective sleep data across approximately 11 days in a large sample of 144 infants. First, this allowed for a comprehensive assessment of sleep behavior while reducing the influence of isolated confounding events of limited duration. Further, the longitudinal design enabled us to study in particular

Table 2
Effects of a change in group (dichotomous variables) or an increment in 1 unit on predictor variables on actigraphy-assessed infants' sleep composites for combined noise during the night.

		Model without interaction terms				Model with interaction term siblings × noise			
		b	S.E.	95% CI	*p*-value	b	S.E.	95% CI	*p*-value
Sleep Duration[a]									
Effect									
Sex (female)		0.03	0.13	−0.24, 0.29	.84	0.03	0.13	−0.22, 0.29	.79
Gestational age (in weeks)		0.12	0.06	−0.005, 0.24	*.06+*	0.11	0.06	−0.004, 0.23	*.057+*
Exact age at assessment (in months)		0.04	0.01	0.02, 0.06	**<.001******	0.04	0.01	0.02, 0.06	**<.001******
Parents' highest educational background	Higher Secondary Education	0.29	0.82	−1.31, 1.90	.72	0.25	0.79	−1.30, 1.80	.75
	University	0.05	0.23	−0.40, 0.51	.81	0.03	0.22	−0.41, 0.46	.91
	PhD	−0.21	0.25	−0.71, 0.29	.40	−0.25	0.25	−0.73, 0.24	.32
Siblings (yes)		−0.1	0.13	−0.36, 0.16	.44	−2.45	0.83	−4.08, −0.82	**.003****
Combined noise (in LAeq, dB)		−0.003	0.01	−0.02, 0.01	.74	−0.02	0.01	−0.04, 0.0004	*.054+*
Siblings (yes) × combined noise						0.05	0.02	0.01, 0.08	**.004*****
Sleep Activity									
Sex (female)		−0.34	0.1	−0.53, −0.15	**<.001*****	−0.34	0.1	−0.53, −0.15	**<.001*****
Gestational age (in weeks)		−0.03	0.04	−0.12, 0.06	.48	−0.03	0.04	−0.12, 0.06	.48
Exact age at assessment (in months)		−0.15	0.01	−0.17, −0.13	**<.001*****	−0.15	0.01	−0.17, −0.13	**<.001*****
Parents' highest educational background	Higher Secondary Education	−0.75	0.58	−1.89, 0.40	.20	−0.75	0.58	−1.90, 0.40	.20
	University	−0.33	0.16	−0.65, −0.01	**.04***	−0.33	0.17	−0.65, −0.005	**.047***
	PhD	−0.34	0.18	−0.70, 0.02	*.06+*	−0.34	0.18	−0.70, 0.02	.06+
Siblings (yes)		−0.2	0.09	−0.39, −0.02	**.03***	−0.11	0.63	−1.34, 1.12	.86
Combined noise (in LAeq, dB)		−0.009	0.006	−0.02, 0.003	.16	−0.008	0.008	−0.02, 0.007	.30
Siblings (yes) × combined noise						−0.002	0.01	−0.03, 0.02	.88
Sleep Variability									
Sex (female)		−0.13	0.12	−0.35, 0.10	.28	−0.13	0.12	−0.35, 0.10	.28
Gestational age (in weeks)		0.005	0.05	−0.10, 0.11	.93	0.005	0.05	−0.10, 0.11	.93
Exact age at assessment (in months)		−0.08	0.01	−0.10, −0.06	**<.001*****	−0.08	0.01	−0.10, −0.06	**<.001*****
Parents' highest educational background	Higher Secondary Education	−0.42	0.70	−1.80, 0.96	.55	−0.41	0.71	−1.80, 0.98	.56
	University	−0.18	0.20	−0.57, 0.21	.36	−0.18	0.20	−0.57, 0.22	.37
	PhD	−0.42	0.22	−0.85, 0.01	*.058+*	−0.41	0.22	−0.85, 0.02	*.06+*
Siblings (yes)		−0.29	0.11	−0.51, −0.06	**.013***	0.12	0.76	−1.38, 1.61	.88
Combined noise (in LAeq, dB)		−0.006	0.007	−0.02, 0.009	.43	−0.003	0.01	−0.02, 0.02	.75
Siblings (yes) × combined noise						−0.008	0.015	−0.04, 0.02	.59

Abbreviations: b = standardized regression coefficient; S.E. = standard error; CI = confidence interval; + $p < .1$, *$p < .05$, **$p < .01$, ***$p < .001$.
[a] Please note that due to the analytic strategy, the composite "sleep duration" no longer has a unit. For details, please see the methods section.

the association between noise and sleep during the dynamic periods of infants' sleep pattern development (Schoch et al., 2020). Last, the sleep parameters derived from actimetry enabled an approach that maximally and comprehensively captured infant sleep parameters and is comparable across development (Schoch et al., 2019, 2020). However, there are some factors that should be taken into consideration when interpreting the results. First, although previous studies did not suggest a general systematic over- or underestimation of the modelled noise exposure (Schlatter et al., 2017), we cannot exclude this possibility. This is primarily due to noise exposure not being modelled inside the sleeping rooms. Furthermore, we lacked information on the position of the bedroom relative to the road or railway lines, and we did not know whether the sleeping room window was open or closed. Besides this, the noise estimates were modelled as yearly averages for 2011. Unlike air pollution, ambient transportation noise is hardly influenced by meteorology and season. Information on window behavior, which differs by season, however, may influence indoor noise levels (Locher et al., 2018). Unfortunately, this information was not available for the cohort, neither was information on the housing situation (e.g., single-vs. multi-family house). Additionally, compared to the guidelines of the World Health Organization (World Health Organization, 2018), noise levels were relatively low, wherefore effects may be larger in other samples. Finally, we focused our analyses on an 8-h time window between 23:00 and 7:00, which may not always correspond to the precise infant sleep period and include some variability across work days vs. weekend days. However, it is a time window during which the likelihood of children sleeping as well as being in the location for which noise was modelled is highest and during which other factors impacting on the infants' sleep are less likely to have biased our results.

5. Conclusion

Our data provide novel evidence that infants' objectively assessed sleep during the first year of life generally seems well-protected against external perturbation, for instance by nocturnal transportation noise. However, individual sensitivity varies: infants who grow up in a sleep-protective environment (for instance without noise from siblings) may be more sensitive to the adverse effects of transportation noise on sleep.

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Ethical approval

Ethical approval was provided by the cantonal ethics commission (Ethikkommission Zürich; 2016-00730). The study was conducted in accordance with Swiss law and the Declaration of Helsinki.

Contributors' statement

Dr Blume analyzed the data, drafted, and revised the manuscript. Dr Schoch collected the sleep data, analyzed the data, and revised the manuscript. Dr Usemann conceptualized the study, drafted, and revised the manuscript. Dr Kurth conceptualized the study, supervised the sleep data collection, and revised the manuscript. Dr Vienneau modelled the noise data and critically reviewed the manuscript for important intellectual content. Drs Röösli, Kohler, and Moeller critically reviewed the manuscript for important intellectual content. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

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.2021.111776.

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