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Decibels and development: How noise exposure at home and school influences early attentional skills

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ABSTRACT

The transition from pre-school to primary school marks a period of rapid cognitive development in children, yet the impact of noise exposure during this stage remains poorly understood. In this longitudinal study, selective and divided attention were assessed in 42 children tested at ages 6 and 7, using subtests of the Intelligence and Development Scales (IDS-2), alongside an extensive personalized noise monitoring campaign. Equivalent sound pressure levels were recorded over several weeks at each child's bedroom façade and inside their classrooms and school cafeterias. Selective attention appeared to depend mainly on individual baseline performance and individual learning curves, while divided attention was significantly associated with noise exposure. At the start of elementary school, higher classroom noise levels were linked to poorer divided attention; however, children in noisier environments showed greater improvement over time, suggesting a catch-up effect during the first school year. Although evening and nighttime noise exposure at home was not a significant baseline factor, it contributed to the observed compensatory pattern through its interaction with time in the linear mixed-effects model. These findings suggest that moderate noise exposure may support the development of more complex attentional skills, such as divided attention, at a young age in a behaviorally typical sample.

1. Introduction

Divided attention refers to the capacity to process and respond to multiple streams of information simultaneously. While selective attention—the ability to focus on one task while suppressing distractions—tends to develop earlier in childhood, divided attention is equally vital and continues to evolve into adolescence and early adulthood (Klenberg et al., 2001; Best and Miller, 2010). In everyday life, children must often follow spoken instructions while manipulating objects, attend to both auditory and visual cues, and manage dynamic social interactions. Consequently, divided attention is a key predictor of learning readiness and adaptive functioning (Baars and Gage, 2010; Mizuno et al., 2013; McDougal et al., 2020; Pineda et al., 2023). As attentional skills constitute the basis of higher cognitive and executive functioning, understanding their mechanisms and determinants warrants dedicated research.

The transition from preschool to primary school marks a period of rapid cognitive growth. In this time frame, children show marked improvements in executive functions (Borghans et al., 2015; Ntousi et al., 2019; Demetriou et al., 2022). These advances, however, also increase sensitivity to environmental factors that may compromise attentional efficiency (Evans, 2006; Munakata et al., 2013; Lynch et al., 2024). Understanding how environmental conditions affect selected and especially divided attention during this developmental window is critical, as children enter more structured and cognitively demanding learning environments at school.

Noise exposure in the home environment can potentially influence children's attentional development, particularly during the evening and night. Evening hours are important for recovery and preparation for the next day's learning demands, while nighttime is essential for high-quality sleep—a prerequisite for e.g. memory consolidation and neural maturation (Reynaud et al., 2019; Morales-Muñoz et al., 2021; Weighall

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and Kellar, 2023). Persistent noise from traffic, neighbors, or household sources can disrupt these processes, leading to cognitive fatigue and impaired daytime functioning. Chronic nighttime noise exposure, in particular, has been linked to reduced sleep quality and duration, with downstream associations with attention and learning (Carter, 1996; Pirrera et al., 2010; Halperin, 2014; Dzhambov et al., 2018). Thus, both evening and nighttime noise represent potential environmental risk factors for attention in young children.

School environments often expose children to elevated sound pressure levels (SPLs) that can challenge attentional control and learning. Excessive noise in classrooms and communal spaces such as lunchrooms may overload auditory processing, heighten cognitive demands, and induce stress. Moreover, poor acoustic properties—especially long reverberation times - can reduce speech intelligibility (Beutelmann and Brand, 2006) and increase cognitive load (Kjellberg, 2004), particularly in children who are still developing efficient auditory and attentional strategies. Both SPL and reverberation time are therefore critical indicators of the acoustic quality of school environments (Dockrell and Shield, 2006; Sato and Bradley, 2008; Shield and Dockrell, 2008; Klatte et al., 2010, 2013; Valente et al., 2012; Mealings, 2021).

Attentional performance, however, is shaped by numerous contextual and individual factors beyond environmental noise. Activity-related factors such as music listening habits may increase auditory load and raise hearing thresholds (Båsjö et al., 2016). Parental reading activities have been linked to improved language development, attentional control, and cognitive resilience (Hindman et al., 2008; Demir-Lira et al., 2019; Horowitz-Kraus et al., 2025). The broader environmental quality of the living environment could be relevant as well: access to greenery and natural spaces, e.g., has been associated with attention restoration (Kaplan and Kaplan, 1989) and stress reduction (Ulrich et al., 1991). Natural surroundings are further known to mitigate self-reported environmental noise annoyance (Van Renterghem, 2019). Household composition can additionally play a role—larger households may increase background noise but also enrich social interactions and affect the amount of parental attention directed to an individual child. Socio-economic status (SES) is known to be strongly associated with overall child development (see e.g. Bradley and Corwym, 2002) but also cognitive performance (intelligence, memory, language skills) (Noble et al., 2007) and, more specifically, attention skills (Hampton Wray et al., 2017). Personal factors might further contribute, such as gender and emotional stability. Hyperactivity is particularly relevant, as hyperactive children tend to be more distractible and struggle with coordinating multiple attentional demands (Fuggetta, 2006; Karatekin et al., 2009; Miklós et al., 2019). Considering these covariates is important to isolate the specific effects of environmental noise on selective and divided attention.

A number of studies have yet looked at the effect of noise exposure at school on general cognitive performance (Stansfeld et al., 2005; Matheson et al., 2010; Bhang et al., 2018), while others considered both school and home noise exposure (van Kempen et al., 2010; Belojevic et al., 2012; Pujol et al., 2014; Foraster et al., 2022). Belojevic et al. (2012) did not find a main effect on executive functioning (teacher-rated items of an attention deficit disorder questionnaire) due to noise exposure either at home or at school, but a negative association between noise levels at home for boys only was observed. Pujol et al. (2014) found that children exposed to higher noise levels at home and school tended to have lower mathematics and language scores. Stansfeld et al. (2005) and van Kempen et al. (2010), both focusing on road traffic and aircraft noise, found a negative association between reading comprehension and recognition memory (Stansfeld et al., 2005), and making more errors on a “Switching Attention Test” (van Kempen et al., 2010). Bhang et al. (2018) reported lower attention and cognitive test performance among school children exposed to artificially added traffic. Foraster et al. (2022) observed that exposure to road traffic noise at school, but not at home, was associated with slower development of working memory, complex working memory, and attention. While most of the aforementioned publications report an association between environmental noise on the cognitive development of children, conclusions regarding the relative importance of school versus home exposure stay mixed.

Another aspect that might rise concerns is the strong reliance on simulated noise exposure such as in Stansfeld et al. (2005), van Kempen et al. (2010) and Pujol et al. (2014). While such an approach enables inclusion of a large number of respondents, the accuracy of these simulations can be questioned. This is particularly relevant in urban environments since errors can be substantial due to complex sound propagation phenomena such as multiple reflections in streets that may be diffusive in nature, meteorological effects like sound refraction and scattering on atmospheric turbulence, and the positioning of bedrooms at shielded building sides. These conditions cannot be captured by the simplified diffraction formulae used in standard noise mapping models such as (International Organization for Standardization, 1996) or CNOSSOS (Kephalopoulos et al., 2012), nor do such models account for roof shape, which alone can already cause differences of up to 10 dBA at shielded façades (Van Renterghem and Botteldooren, 2010). Further note that those simulated noise maps only account for traffic related environmental noise sources. In an urban environment, recreational noise, construction noise, noise from neighbors and noise from heating, ventilation and air conditioning (HVAC) equipment can be important as well for the actual exposure.

In the study by Belojevic et al. (2012), measurements were conducted, but only during a few hours and can therefore be considered “snapshot” assessments, limiting its generalizability to long-term exposures. Moreover, these measurements were taken in the middle of the street where the children lived and at one outer façade of the school. Foraster et al. (2022) made noise measurements indoors and outdoors at the schools involved in their study over short time intervals (30 min) as well, during two consecutive days. To assess home exposure, however, they relied on simulated road traffic noise maps.

The review article by Gheller et al. (2024) further stipulates the scarcity of longitudinal studies, limiting the ability to draw robust conclusions about noise effects on children's cognitive development. Except for Foraster et al. (2022), the aforementioned studies are all cross-sectional.

In response, the present study investigates how environmental noise at home and in school environments influences children's performance on selective and divided attention. To the authors' knowledge, such studies have not yet been reported. By focusing on the same group of children before and after the transition from preschool to primary school, the study examines how developmental changes interact with noise exposure in shaping attentional performance during this critical period. A key strength of the research lies in its longitudinal design and reliance on detailed individual noise exposure measurements. For each child, noise exposure was continuously monitored over several weeks, both at home and at school. This approach provides a comprehensive and ecologically valid assessment of the relationship between individual noise exposure and selective and divided attention in early childhood.

2. Methodology

This study was reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines.

2.1. Participant recruitment

The study's aims and procedures were communicated to local primary schools via e-mails, reminder e-mails and phone calls. For schools showing some interest, researchers arranged individual meetings with school administrators and teachers. Once participation by a school was confirmed, parents of third-grade preschool children (the year before entering primary school) received detailed study information together with a form to indicate their willingness to participate. Researchers then held group sessions—either online or in person—with parents to explain the study design and objectives in more detail, and to obtain informed consent. Ethical approval was granted by the local Ethics Commission (Vote No. ONZ-2022-0058, April 26, 2022), in accordance with the Belgian law of May 7, 2004, on research involving human participants.

Because several weeks of noise measurements were planned for each respondent and the number of available sonometers was limited, the number of participants was restricted to about 40 to keep data collection and equipment requirements manageable. Recruitment therefore began in the wider region of Ghent (Belgium), with the search area gradually expanded to achieve the target sample size. In total, 35 schools were contacted, of which 12 agreed to participate. A flow diagram illustrating the selection and inclusion of study participants is provided in Fig. 1.

2.2. Cognitive testing

Selective attention was assessed using the Intelligence and Development Scales (IDS-2) Subtests 3 and 15 (Grob et al., 2018). In Subtest 3 (visual selective attention), participants had 2 min to cross out items with two specified features from an array of similar distractors. Correct responses yielded +1 point and errors −1 point. In Subtest 15 (verbal selective attention), participants generated as many words as possible within 90 s from the categories "animals" and "food". Repetitions or incorrect responses resulted in a 1 point penalty. Scores from both tasks were first age-normed (z-scored) and then averaged.

Divided attention was measured with Subtest 16, which combines the two selective attention tasks. Within 2 min, participants crossed out specified parrots while simultaneously generating words from the semantic category "animals". Performance of both tasks were first age-normed (z-scored) and averaged to yield the divided attention score. All cognitive tests were individually performed at school in a quiet, but non-soundproof room.

2.3. Environmental noise levels at home

Continuous façade sound pressure level measurements were conducted outside the child's bedroom. At each dwelling, measurements were performed during a period between 2 and 4 weeks. The sound measurements were performed with internet-based noise nodes. It was previously shown that such devices can be accurate to within 1 dBA, relative to (reference) type-1 equipment, for environmental noise monitoring (Van Renterghem et al., 2011).

The sonometers were positioned on the window sills or attached to balustrades in case of balconies. Depending on the position of the dominant environmental noise sources in the neighborhood, façade reflections might be substantial. Sound pressure levels increases from 3 to 6 dBA, relative to incident sound, for road traffic noise sources, could be expected (Hall et al., 1984; Memoli et al., 2008; Mateus et al., 2015; Barrigón Morillas et al., 2016). In this study, the uncorrected sound pressure levels will be used.

Based on the basic 1/8 s 1/3 octave band measurements, cumulative A-weighted equivalent sound pressure levels were calculated over subsequent evening and night periods, to end up with a façade noise exposure consistent with the concept of a noise dose. For the night periods, equivalent sound pressure levels for individual nights were calculated as well, and the minimum and maximum results at each location, over the full measurement period, were searched for.

Note that the definition of the evening and night period used here deviates from similar environmental noise indicators as defined in the Environmental Noise Directive (European Parliament and Council, 2002). Given our focus on young children, the evening period is defined between 16:00 and 20:59, while the night period stretches from 21:00 till 6:59 next morning.

All evening and nights periods were considered during the measurement period, including those falling in the weekends. Daytime exposure during Wednesday afternoons (common half-day off in the region under study) or weekends were not considered, given daytime periods are potentially less noise sensitive moments. In addition, it is less likely that the children were actually at home, in contrast to evening and night periods.

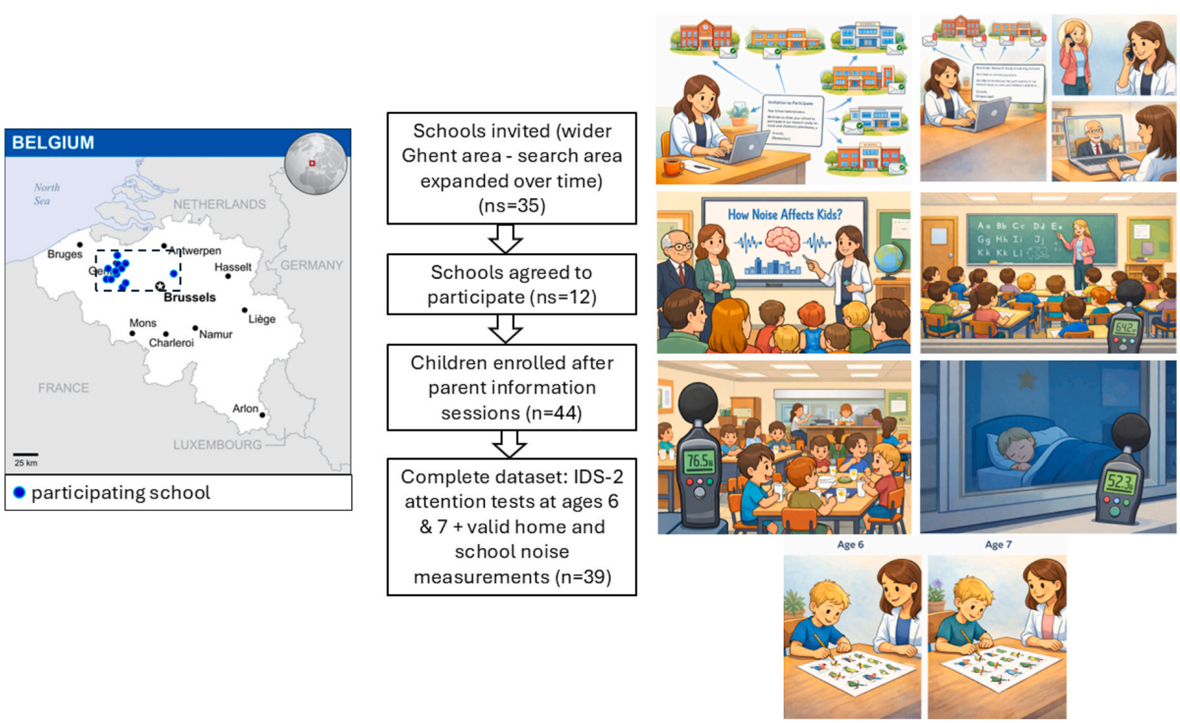

Fig. 1. Flow diagram illustrating the selection and inclusion of study participants.

2.4. Acoustic characterization in the educational setting

Continuous sound pressure level measurements were conducted inside both classrooms and cafeterias (lunchrooms), over periods of 2 to 3 weeks. Equivalent continuous sound pressure levels were calculated based on the expected presence of pupils in these rooms, as derived from school timetables. Time periods in which the regular schedule was disrupted (e.g., school excursions) were identified through consultation with teachers and excluded from the analysis. The goal is to measure the actual sound exposure during a typical school day (so including exposure due to teacher/pupil interactions), with occupied rooms, and not so much (outside) environmental noise entering the room.

The continuous sound pressure level measurements during room occupancy were supplemented with reverberation time measurements. More precisely, the measurements relied on RT20, the time required for the sound to decay by 20 dB from − 5 dB to −25 dB relative to the maximum sound pressure level measured upon exciting an impulsive test signal. This time is then linearly extrapolated to a 60 dB decay, defining the reverberation time of the room. The measurements were made using a type-1 accredited measurement chain consisting of a sonometer SVANTEK 959, a ½" microphone capsule and a pre-amplifier. As a sound source, repeated balloon popping was performed, which is recognized as an efficient yet sufficiently accurate approach (Christensen et al., 2013). Reverberation time measurements were performed in non-occupied rooms, with 5 repetitions after which reverberation times were linearly averaged per octave band. The spectral RT results were then further reduced to a single number by linearly averaging over the 500 Hz, 1000 Hz and 2000 Hz octave band, following ANSI/ASA S12.60-2010 (2010).

The continuous sound pressure level measurements provide a dosimeter-like estimate of pupil exposure. Instead of equipping each child with an individual portable dosimeter—which is highly impractical at this age—the room-level measurements serve as a proxy. Moreover, this method allows the simultaneous assessment of exposure for multiple pupils within the same class group. Measurements were performed in the period between the two cognitive assessment tests and were considered representative of the exposure during this interval.

2.5. Personal, social, and other physical exposure factors

Via a parent questionnaire, a range of personal, social, and non-noise related physical exposure factors were assessed, including an inquiry of a number of leisure activities.

Parental stress, which is closely linked to children's stress levels in this age group (see e.g. Anthony et al., 2005; Jiang et al., 2022), was measured using the Perceived Stress Scale (Cohen and Janicki-Deverts, 2012). This widely used instrument captures the extent to which parents perceive situations as stressful, unpredictable, or overwhelming. Respondents rated their experiences over the past month on a one-to-five Likert scale, with higher scores indicating greater perceived stress. The 10 individual item scores were averaged to yield a single mean score representing overall parental stress.

Child socio-emotional functioning was measured with the Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997). Two dimensions were considered in this work: Hyperactivity/Inattention, indicated as *SDQ_hyperactivity* (restlessness, overactivity, distractibility, difficulty sustaining attention) and Emotional Symptoms as *SDQ_emotional* (worries, fears, somatic complaints, feelings of unhappiness). Each scale comprises five items rated on a three-point Likert scale (not true, somewhat true, certainly true), with summed scores ranging from 0 (not emotional or hyperactive at all) to 10 (strongly emotional or hyperactive).

Residents' perceptions of the quality of their living environment (EnvQual, Leist et al., 2024) were also assessed, using a four-point Likert scale (completely agree, mostly agree, mostly disagree, completely disagree). Items addressed domains such as child safety (e.g., traffic danger, safe street crossing), opportunities for play and peer contact (e.g., outdoor play without supervision, playground availability, presence of nature), and neighborhood infrastructure (e.g., maintenance of public spaces, presence of trees, bicycle paths, local amenities, school accessibility). Additional items covered social cohesion (e.g., meeting neighbors, mutual help), housing and aesthetic quality, and environmental stressors (e.g., traffic, neighbor and industrial noise, air pollution, littering). Respondents also rated their sense of safety, comfort, and overall well-being in the neighborhood. Responses to these 26 items were averaged into a single score ranging from 1 to 4, with higher scores indicating a high-quality self-reported living environment.

In addition, information was collected on *Gender*, children's use of personal music players (*MusicPlayerUse*), and the frequency with which parents read stories to them (*Read2kids*). Listening to intense music may represent a relevant source of sound exposure, while being read to influences literacy and cognitive development (Hindman et al., 2008; Demir-Lira et al., 2019; Horowitz-Kraus et al., 2025). Household size (*HouseholdSize*), or the number of people living within the family house, was asked for as well.

As a summarizing construct of socio-economic status, that can be correlated to objective assessments (Adler et al., 1994, 2000), participants were asked to imagine a ladder with ten rungs representing their position relative to other residents in Belgium (*SESLadder*). Those at the top have the most money, highest education, and best jobs. Those at the bottom have the least money, lowest education, and worst jobs—or no job at all. The parent survey further inquired whether someone is smoking inside the house, and whether there were hearing issues/medical interventions with relation to the child.

Together, these potential covariates reflect multiple aspects of the child's exposome (see e.g. Persson Waye et al., 2023 for its definition), with assumed relevance to attention performance. The aim was to position noise-related exposures in relation to a sufficient set of such broader factors. This set, based on prior knowledge and grounded in relevant literature, is not complete and could be further extended.

2.6. Statistical analysis

We examined the influence of environmental and personal predictors on children's cognitive outcomes using linear mixed-effects models (LME). This approach was selected because the data were longitudinal, with repeated cognitive assessments at baseline and one-year follow-up. The LME framework accounts for within-child correlations (i.e., each child's individual baseline level) and between-child variability in developmental trajectories (i.e., individual learning curves) by including random intercepts and random slopes for time at the child level (1 + TimeNum | ChildID). The variable TimeNum was dummy-coded to represent the measurement occasion (0 = baseline, 1 = follow-up), allowing the model to capture both baseline differences between individuals and individual variability in change over time. Each model included fixed effects for the predictor of interest, the main effect of time (TimeNum), and their interaction (Predictor × TimeNum). This structure enabled estimation of the effect of the predictor on baseline outcome levels, the average change in outcomes from baseline to follow-up, and whether this change over time varied systematically as a function of the predictor.

Given the relatively large number of potential predictors and a limited sample size (N = 42x2), we applied a two-step collinearity check to reduce instability due to multicollinearity. After an initial and careful selection of predictors, we applied z-scoring and collinearity was further assessed based on variance inflation factors (VIF). Predictors with VIF larger than or equal to 5 were excluded prior to model fitting. Secondly, after each round of model simplification (see below), VIF values were recomputed to ensure no new collinearity had been introduced as predictors were removed.

Model selection proceeded via an iterative elimination procedure. Starting from a full model including all relevant predictors and their interactions with time, predictors were removed step by step. At each step, the predictor with the highest p-value (provided $p > 0.05$) was flagged for removal. However, to avoid discarding variables that contributed meaningfully to overall model fit, regardless of their individual p-values, each candidate elimination was additionally evaluated using a likelihood ratio test (LRT) comparing the model including the flagged predictor against the model without it. Predictors were retained if their removal led to a significant reduction in model fit, even when their individual effect was not statistically significant at the 5% level. This combination of p-value–based testing and LRT-based model comparison ensured that the final reduced model preserved predictors that contribute to explanatory power.

To evaluate the robustness of the final model given the limited sample size, we implemented a leave-k-out procedure. Specifically, the full iterative model selection process was repeated 100 times, each time after randomly removing three participants (meaning 6 datapoints). Predictors that were consistently retained across these subsamples were considered reliable. As a criterion, a predictor was considered robust if it was retained in at least 90% of the iterations, and if in 80% of those cases its p-value was below 0.05 and 90% below 0.10. Although the final model was estimated with all participants, the leave-k-out procedure confirmed that the set of final predictors did not overly depend on particular individuals and were therefore stable across subsamples. This allowed checking whether convergence was reached, and to see whether final predictors remained statistically significant even when estimated on slightly smaller samples of respondents.

Because of the relatively large number of potential predictors and covariates tested relative to the number of participants, we applied a multiple-testing correction to reduce the risk of false positives. For the final reduced model, p-values of fixed effects were adjusted using the Benjamini and Hochberg (1995) false discovery rate (FDR) procedure. Predictors were considered robust if they remained statistically significant.

This combined strategy—longitudinal LME modeling, systematic collinearity control, iterative simplification via p-values and likelihood ratio tests, robustness checks via the leave-k-out procedure, and conservative multiple-testing correction—ensure that reported predictors reflected stable associations rather than spurious statistical artifacts.

3. Results

3.1. Test panel description

A total of 44 children participated in this study from twelve different schools (see Fig. 1). The attention tests were completed by all participants at the end of preschool (May–June 2022) or at the beginning of primary school (September–October 2022), at a mean age of 6.0 years (SD: 0.4 years). The follow-up tests were performed at a mean age of 7.0 years (SD: 0.4 years); two children changed school between baseline and follow-up testing and were consequently excluded from the dataset, leading to 42 valid participations.

For selective attention, the (non-age normalized, non-z-scored) mean and median scores were 23.9 and 24.5 (SD = 8.0) at baseline, and 30.6 and 30.3 (SD = 7.2) during the follow-up test about one year later, respectively. For divided attention, the mean and median scores were 10.9 and 11 (SD = 5.0) at baseline, and 14.5 and 14 (SD = 5.3) at follow-up.

There were 26 girls and 16 boys participating in the test panel (see Fig. 2), mostly children living in a 4-person household (48%), in parent self-rated high quality neighborhoods (M = 3.2, SD = 0.4, on a 1-to-4 scale). The parents position themselves almost exactly in the middle of the SES ladder (M = 4.9, SD = 2.2, on a 1-to-10 scale). The mean score on the parental perceived stress scale was 2.5 (SD = 0.5, on a 1-to-5 scale). Overall, the parents seem active in reading to their kids (64% declared to do this almost daily). More than half of the kids listened less than once a week to personal music players.

The SDQ for the emotional dimension resulted in a mean of 1.9 (SD = 1.5) and a hyperactivity mean rating of 3.3 (SD = 2.3), both on a zero-to-ten scale. All parents declared that no one is smoking inside the house. None of the parents reported hearing loss in the questionnaire responses regarding their children. However, eleven children (26%) underwent the placement of ventilation tubes due to recurrent otitis media.

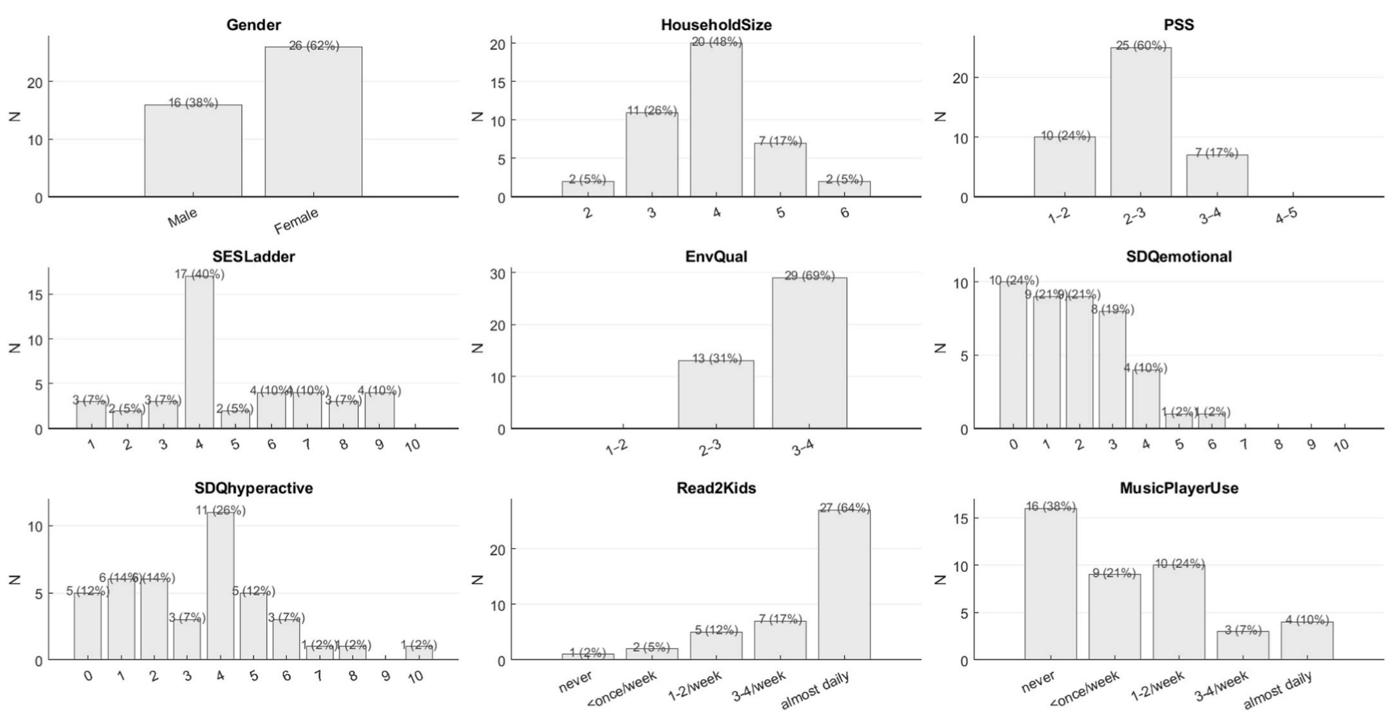

Fig. 2. Distribution of potential covariates over the test panel that were considered in the statistical modelling (N = 42).

3.2. Measured noise indicators

3.2.1. At home

In total, façade noise level measurements were made at 44 dwellings; 2 pupils lived during the monitoring period at both the father's and mother's house, for which the exposure indicators were linearly averaged, regardless of the actual duration in either dwelling. At three locations, the façade noise measurements failed or measurements were corrupted, leaving us with 39 pupils that could be assigned a noise home exposure; the linear mixed effect modelling (see Sections 3.4 and 3.5) is consequently performed for these 39 participants with combined two-time attention testing (see Section 3.1) and valid noise exposure measurements at home.

In the current research, the goal was to assess the long term noise exposure between baseline and follow-up cognitive testing, which was one year apart, based on a more limited measurement duration of several weeks. Therefore, convergence is a key metric. As a convergence criterion, the equivalent sound pressure levels using the first 80% of the time series was compared to the complete time series. Across all locations, this analysis yielded a root-mean-square difference of 0.4 dBA (mean of 0.3 dBA, SD = 0.2 dBA) for evening periods, and 0.6 dBA (mean of 0.4 dBA, SD = 0.5 dBA) for night periods. Note that this is well below the accuracy limit of the sound level meters, indicating that the measurement duration was sufficiently long to converge to the typical outdoor exposure at the bedroom facade.

Given the child-centered definition for evening and night hours, including still busy periods at the beginning of the night, long-term equivalent levels were quite similar for evening and nights.

3.2.2. At school

In total, measurements were performed in 37 rooms across 12 schools, including both classrooms (24) and cafeterias (lunchrooms) (13), over periods of 2–3 weeks.

Especially in the school environment, the convergence of long-term equivalent sound pressure levels should be checked given the rather limited presence in some rooms, especially regarding the cafeterias. Across all class rooms and cafeterias, this analysis yielded a root-mean-square difference of 0.5 dBA (mean of 0.1 dBA, SD = 0.5 dBA), indicating that also in the school environment, the measurement duration was sufficient to converge to the typical pupil exposure in these rooms.

As an illustration, in Fig. 3, left pane, the distribution of the candidate noise exposure indicators for the statistical modelling is shown over all children in both the educational setting (indoors) and at home (outdoors). The class and cafeteria exposure are supplemented by the total exposure during the school day by time-weighting the expected duration of presence in both types of rooms. In the right pane, reverberation time measurements are shown in the classes and cafeterias. Table 1 gives an overview of the characteristics of the children included in this study.

3.3. Selection of noise exposure predictors

To aid avoiding collinearity issues in the statistical modelling, a preselection of noise indicators was made based on the correlation matrix presented in Fig. 4. Although VIF tests are consistently performed, this allows assessing the relevance of the same indicators, especially relevant in case of the leave-k-out analysis.

We retained Noise_home_LAEQevening, Noise_class_LAeq, and Noise_cafetaria_LAeq. All home-related exposure indicators are moderately to strongly correlated (>0.5), and this holds for levels during both evening and night.

Noise_school_LAEQ is a time-weighted combination of Noise_class_LAEQ and Noise_cafetaria_LAEQ and correlates well with these indicators. Noise_class_RT20 was moderately correlated with Noise_class_LAeq. Noise_cafetaria_RT20 was excluded as well, to keep the model sufficiently lean, although correlation coefficients with other school noise indicators were limited (<0.5).

The statistical modelling procedure thus starts from the following equation. In this notation, for brevity, same predictors without time interactions were equally evaluated:

Outcome ~ TimeNum× (Noise_home_LAEQevening + Noise_class_LAEQ + Noise_cafetaria_LAEQ + SDQ_emotional + SDQ_hyperactivity + Gender + HouseholdSize + PSS + EnvQual + MusicPlayerUse + Read2kids) + (TimeNum|ChildID)

In the modelling efforts, TimeNum and the random slope and intercept for ChildID are always retained because they capture the essential longitudinal structure of the study. The minimum model is therefore:

Outcome ~ TimeNum + (TimeNum|ChildID)

TimeNum reflects systematic change between baseline and follow-up, while the random-effects term accounts for individual differences in starting level and rate of change. These components cannot be subjected to backward elimination, as removing them would break the repeated-measures structure, inflate dependencies within children, and bias estimates. They are thus required regardless of which environmental predictors are evaluated.

3.4. Selective attention

The linear mixed-effects model for selective attention retained home evening exposure together with their time interaction as fixed effects, in

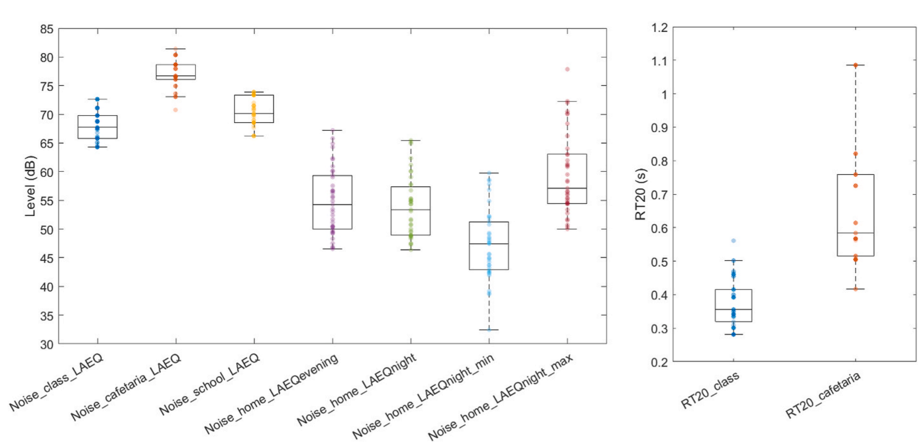

Fig. 3. Noise exposure characteristics over all children in both the educational setting (class rooms and cafeterias, indoors, occupied) and at home (during the evening and night, outside the child's bedroom façade, not corrected for façade reflections). On the right pane, the RT20 distributions are depicted in the class rooms and cafeterias (unoccupied).

Table 1
Characteristics of the children that were included in the current study, their noise exposure at home and in the school environment, and the results of the selective and divided attention testing.

N = 42		Number	Percentage	Mean	Std	Median	Inter Quartile Range
Gender	boys (coded as 1)	16	38.1%				
	girls (coded as 2)	26	61.9%				
Age IDS-2 test	at baseline (years)			6.02	0.38	5.94	0.44
	at follow up (years)			7.01	0.39	6.90	0.46
HouseholdSize				3.90	0.91	4	1
PSS (1 to 5 scale)				2.47	0.53	2.55	0.80
SESladder (1 to 10 scale)				4.90	2.24	4	3
EnvQual (1 to 4 scale)				3.17	0.37	3.17	0.58
SDQemotional (0 to 10 score)				1.86	1.54	2	2
SDQhyperactive (0 to 10 score)				3.31	2.31	4	4
Read2Kids	never	1	2.4%				
	less than once a week	2	4.8%				
	1-2 times a week	5	11.9%				
	3-4 times a week	7	16.7%				
	almost daily	27	64.3%				
MusicPlayerUse	never	16	38.1%				
	less than once a week	9	21.4%				
	1-2 times a week	10	23.8%				
	3-4 times a week	3	7.1%				
	almost daily	4	9.5%				
Noise at school	Noise_class_LAEQ (dB)			68.1	2.6	67.7	4.0
	Noise_cafetaria_LAEQ (dB)			76.9	2.4	76.7	2.5
	Noise_school_LAEQ (dB)			70.4	2.4	70.1	4.8
	RT20_class (s)			0.38	0.07	0.36	0.10
	RT20_cafetaria (s)			0.67	0.19	0.58	0.24
Noise at home[a]	Noise_home_LAEQevening (dB)			54.8	5.8	54.3	9.3
	Noise_home_LAEQnight (dB)			53.8	5.4	53.4	8.4
	Noise_home_LAEQnight_min (dB)			47.3	6.1	47.4	8.3
	Noise_home_LAEQnight_max (dB)			59.5	7.0	57.1	8.5
IDS-2 scores selective attention	at baseline			23.9	8.0	24.5	11.5
	at follow up			30.6	7.2	30.3	10.5
IDS-2 scores divided attention	at baseline			10.9	5.0	11.0	6.5
	at follow up			14.5	5.3	14.0	7.0

[a] N = 39.

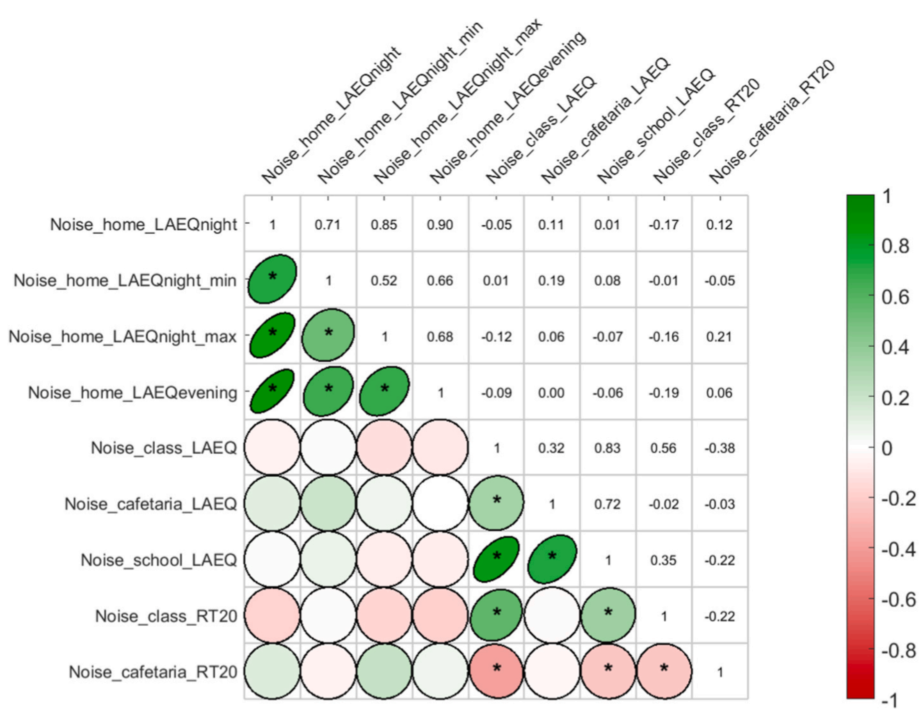

Fig. 4. Correlation matrix of the measured home and school noise exposure related parameters. The * indicate whether the linear correlation between each pair of indicators is statistically significant at the 5% level. Pearson's correlation coefficients are represented by both the color coding, the shapes (line over ellipse to circle), and their values (presented above the diagonal of the matrix).

addition to the predictors of the minimum model (see Section 3.3):

Attention_sel ~ TimeNum + Noise_home_LAEQevening + TimeNum×Noise_home_LAEQevening + (TimeNum|ChildID)

Model statistics are summarized in Table 2. Significant predictors were not found, although noise at home, and its time interaction, aid building up the statistical model. There is no significant overall improvement between baseline and follow-up testing for selective attention scores. The explained variance appears to stem primarily from individual differences in baseline performance and individual learning trajectories.

3.5. Divided attention

The linear mixed-effects model for divided attention retained home evening noise exposure, classroom noise exposure, gender, and perceived environmental quality as fixed effects, along with their interactions with time:

Attention_div ~ TimeNum + Noise_home_LAEQevening + TimeNum×Noise_home_LAEQevening + Noise_class_LAEQ + TimeNum×Noise_class_LAEQ + Gender + TimeNum×Gender + EnvQual + TimeNum×EnvQual + (TimeNum|ChildID)

Table 3 shows that significant main effects, without time interactions, are gender and noise exposure in class, both robust on the basis of the leave-k-out procedure using the 90% inclusion rule, 80% significance level at 0.05, and 90% at 0.1. With larger exposure to noise levels in class, scoring on the divided attention test is lower. In the current dataset, girls (coded as Gender = 2) seem to perform worse on this type of task than boys (Gender = 1). The Benjamini–Hochberg adjusted p-values remain significant for gender and noise exposure in class. Similarly as with the selective attention test, there is no significant overall change between baseline and follow-up testing for divided attention.

Interactions with time for noise exposure in class, noise at home, and environmental quality show strong significance, and are all robust. Although the façade noise exposure at home and perceived environmental quality at home are not significant as a main effect, they do modulate the trajectory between baseline and follow-up divided attention testing. The positive interaction term indicate that over the one-year period considered, children in noisier environments showed greater improvement in this cognitive outcome than those in quieter environments.

While environmental quality did not significantly predict the baseline cognitive score, its positive interaction with time indicates that children in higher-quality environments showed stronger cognitive improvement across the one-year period. This suggests that environmental quality may facilitate divided attentional development over time, even if initial differences are small or absent.

4. Discussion

4.1. Main findings

At baseline, higher noise exposure in class is linked to poorer divided attention as assessed by the IDS test. Yet, children in noisier environments show stronger improvement over time, suggesting potential adaptation or catch-up effect. The combination of a negative main effect and positive time interactions reflects that while noise initially impairs performance for pre-elementary school children, its relationship diminishes—or even reverses—across the first year in elementary school. This suggests that children may adapt or develop compensatory strategies over time. The noise exposure at home is not statistically significant as a baseline effect, but seem to add to these acquired compensation strategies.

For selective attention, none of the predictors considered reached statistical significance in the final model, with relatively large p-values throughout. The explained variance thus appears to stem primarily from individual differences in baseline performance and learning trajectories, which are captured by the random effects structure (i.e., child-specific intercepts and slopes). In contrast, divided attention, a cognitive more demanding task, seems to be much more influenced by the sonic environment. Coordinating multiple inputs effectively, essential for learning, starts to become important when children enter primary school, when the development of these skills accelerates.

A higher overall self-reported environmental quality at home, as perceived by the parent, appears to contribute to the development of divided attentional skills. In this case, only the interaction with time is statistically significant, indicating that children growing up in higher-quality environments, as perceived by the parents, show greater improvement in divided attention within the specific time frame examined in this study. It should be noted, however, that the overall environmental quality indicator is to some extent negatively correlated with noise exposure at home, although this correlation remained below the variance inflation threshold of 5 applied during the iterative model-building process in order to avoid collinearity issues.

4.2. Comparison with previous literature

The current study adds to the existing body of research dealing with the effect of noise exposure, both at home and school, on cognitive performance. Belojevic et al. (2012) did not find a main effect on executive functioning due to noise exposure either at home or at school in their cross-sectional study, but a negative association between noise levels at home for boys only. The cross-sectional study of Pujol et al. (2014) showed a negative association of noise exposure at home and school on mathematics and language scoring. The longitudinal study of Foraster et al. (2022) observed that exposure to (road traffic) noise at school, but not at home, was associated with slower development of working memory, complex working memory, and attention. The current longitudinal study suggests that both noise exposure at school and at home are relevant, but in a nuanced way. At elementary school entry, noise exposure at school, but not at home, is negatively associated with divided attention. However, both noise at school and at home might help to achieve the observed catch-up effect during this specific developmental period.

The various approaches to assess attentional skills make a comparison between different studies not straightforward. While in Belojevic et al. (2012) attention was assessed indirectly via teacher evaluations, van Kempen et al. (2010), Foraster et al. (2022) and the current work make use of performance tests. The Switching Attention Test (SAT) and the Attentional Network Test (ANT) used in the former two studies were purely visual and could be categorized under selective attention. The Intelligence and Development Scale (IDS-2), as used in current work,

Table 2
Linear mixed effect model results for selective attention.

Selective attention	AIC = 176.01, BIC = 194.87 and Deviance = 160.01						
Predictor	β (Estimate)	SE	t	p-value	95% CI (Lower–Upper)	BH adj. p	Robust (90%-80%-90%)
(Intercept)	−0.576	0.122	−4.737	1.02E-5 ***	−0.818 to −0.334	—	Yes
TimeNum	0.132	0.121	1.098	0.276	−0.108 to 0.373	—	No
Noise_home_LAeq_ev	0.065	0.122	0.528	0.599	−0.179 to 0.308	0.599	No
TimeNum × Noise_home_LAeq_ev	−0.083	0.121	−0.684	0.496	−0.325 to 0.159	—	No

Table 3
Linear mixed effect model results for divided attention.

Divided Attention	AIC = 144.03, BIC = 177.02 and Deviance = 116.03						
Predictor	β (Estimate)	SE	t	p-value	95% CI (Lower–Upper)	BH adj. p	Robust (90%-80%-90%)
(Intercept)	−0.050	0.085	−0.589	0.558	−0.218 to 0.119	—	No
TimeNum	0.032	0.083	0.379	0.706	−0.134 to 0.198	—	No
Gender	−0.294	0.086	−3.422	0.001**	−0.465 to −0.122	0.004**	Yes
Noise_class_LAEQ	−0.212	0.088	−2.400	0.019*	−0.387 to −0.036	0.038*	Yes
EnvQual_mean	−0.126	0.096	−1.316	0.193	−0.318 to 0.065	0.257	No
Noise_home_LAeq_ev	0.052	0.096	0.546	0.587	−0.139 to 0.243	0.587	No
TimeNum × Noise_class_LAEQ	0.25	0.087	2.887	0.005**	0.077 to 0.424	—	Yes
TimeNum × EnvQual_mean	0.331	0.094	3.500	8.27E-4***	0.142 to 0.519	—	Yes
TimeNum × Gender	−0.039	0.084	−0.463	0.645	−0.208 to 0.129		No
TimeNum × Noise_home_LAeq_ev	0.229	0.094	2.429	0.018*	0.041 to 0.416	—	Yes

defines selective attention as a combination of a (separate) visual and a (separate) verbal test, while the divided attention combines both. Interestingly, the more complex portion of the SAT was found to be more susceptible to the effects of noise than its simpler parts following van Kempen et al. (2010). This is consistent with the current observation that for divided attention, a more cognitive resources taxing task, environmental noise exposure is relevant, but not for selective attention.

The work by Bhang et al. (2018) focused on attentional performance *during* exposure to environmental noise and is not further discussed here. In contrast, van Kempen et al. (2010), Foraster et al. (2022) and the current study looked at potentially long-lasting link with attention, by executing the test in a quiet room or with ear caps, so independent of the common school/home noise exposure. Another difference between these studies is the specific interest here in the attentional development over the first year of attending elementary school (so between 6 and 7 year old). In Belojevic et al. (2012), van Kempen et al. (2010) and Foraster et al. (2022), ages ranged from 7 years up till 11 years.

4.3. Children's noise exposure

A key achievement of the present study lies in the detailed characterization of children's noise exposure, including outdoor bedroom façade measurements at 44 dwellings and indoor measurements in 37 rooms across 12 schools. Convergence toward long-term equivalent sound pressure levels was achieved within a measurement period of two to 3 weeks at each location, with a root-mean-square deviation of approximately 0.5 dBA when considering only 80% of the time series relative to the full dataset — a simplified yet robust convergence criterion. This deviation is notably smaller than the measurement accuracy of the equipment used. Overall, the measurement campaign spanned nearly an entire year between the baseline and follow-up cognitive assessments. The fact that convergence was reached supports the conclusion that a few weeks of noise exposure measurements provide a reasonably representative estimate of the child's exposure during the period between baseline and follow-up testing. However, longer-term changes in the noise exposure that extend beyond the several-weeks measurement window could not be evaluated. Especially locations with lower equivalent sound pressure levels could be affected, on condition the measurement period would be atypical.

The median (uncorrected) façade noise exposure level at the dwellings—54 dBA in the evening and 53 dBA at night—is relatively low for the Flanders region, particularly considering that the sound level meters were positioned directly on the façade. This setup typically results in an amplification of 3–6 dBA for road traffic noise (see Methodology Section). Repeated measurements of road traffic exposure throughout the Flanders region indicate that approximately 70 % of dwellings experience levels exceeding 55 dBA (Van Renterghem et al., 2012). Within the framework of the Environmental Noise Directive (END, 2002), strategic noise mapping is in fact only conducted from 55 dBA (L_{den}) and 50 dBA (L_{night}) upwards. Additionally, the median level of the quietest night across all dwellings was 47 dBA, confirming that the current dataset is skewed toward lower noise exposure levels.

Nevertheless, even within this relatively narrow exposure range—where 50 % of the data fall between 50 and 59 dBA for evening levels—home noise exposure was retained in the statistical modeling. Interestingly, moderate levels of environmental noise exposure may have beneficial effects on divided attention tasks, possibly reflecting the development of noise suppression mechanisms in the child's brain. However, this interpretation should not be generalized to higher exposure levels, where the positive effects of quiet evening and night periods—vital for adequate rest, memory consolidation, attention regulation, and broader cognitive development in children—may be undermined by persistent noise.

At baseline, higher classroom noise levels were associated with lower divided attention, suggesting that children entering the first year of school may not yet possess fully developed noise suppression mechanisms. Despite generally good acoustic conditions, with reverberation times all well below the maximum advised limits of 0.6-0.7s for "core learning spaces" following ANSI/ASA S12.60-2010 (2010), the additional auditory load in noisier classrooms likely taxes attentional resources in the early phase. The significant positive interaction with time, however, indicates that children in these environments may adapt by strengthening attentional control over the school year, consistent with the gradual development of auditory filtering and cognitive resilience to environmental noise. It's also possible that noisier classrooms reflect more socially active or dynamic learning environments. While this may initially reduce concentration, over time it could stimulate multitasking and divided attention capacities.

In the occupied classrooms, 50 % of the noise exposure levels ranged between 66 and 70 dBA. Such moderate exposure is not necessarily detrimental as shown in this work. Note that the current measurements do not allow to distinguish between environmental noise penetrating the class room and the sound exposure due to common class activities. But similar to the noise exposure at home, the current findings should not be extrapolated to excessive exposure levels, as they are likely to compromise attentional functioning and learning, so again reversing the association.

The cafeterias in the participating schools were characterized by both high reverberation times (50% having a RT20 between 0.5 and 0.8 s, and a few exceeding 1 s) and elevated noise exposure levels, although these two acoustic parameters were not linearly correlated. The relatively high noise levels observed — with 50% of measurements between 75 and 80 dBA — are unlikely to provide a restorative environment for attentional recovery during lunch breaks. However, given the short duration of exposure in these spaces (typically about 30 min per school day), their overall contribution to the total daily school exposure is limited. When cafeteria noise exposure was included as a candidate predictor, it was not retained in the final models after backward elimination, neither for selective nor for divided attention outcomes.

4.4. Test sample

The sample represents a middle-class population. Participants report an average position of 4.9 on a 1-to-10 socio-economic ladder, typically live in four-person households, and most parents engage in daily reading activities with their children. They express high satisfaction with their neighborhood (mean score of 3.2 on a 1-to-4 scale) and are exposed to comparatively low environmental noise levels. The test panel has a score of 2.5 on the perceived stress scale (PSS), close to the average score of 2.6 over the large sample of 2000 respondents reported by Cohen and Janicki-Deverts (2012).

The Strengths and Difficulties Questionnaire (SDQ) results indicate that the test population exhibited few emotional or hyperactivity problems. According to Bryant et al. (2020) and Vugteveen et al. (2022), SDQ *emotional* scores up to 4 are considered normal to borderline, applying to 96% of the children in our test population. For *hyperactivity*, scores between 0 and 5 are considered as the normal range or borderline, holding for 87% of the participants. The respondents can thus be considered as a behaviorally typical test sample. In this range, SDQ scores were not retained as a confounder in the statistical analysis. Consequently, any conclusions drawn here apply only to the low-score range, where emotional and hyperactivity problems appear to have little influence on attentional outcomes. However, this does not imply that such factors are unimportant—differences might well emerge in a more balanced sample including children with higher SDQ scores.

4.5. Limitations

A key limitation of the present study directly stems from the extensive sound monitoring campaign, which constrained the maximum number of participating children (n = 42). The available sample size limits statistical power, and is insufficient to support stratified analyses to evaluate potential effect modification. While in studies relying on simulated noise levels (Stansfeld et al., 2005; van Kempen et al., 2010; Pujol et al., 2014; Foraster et al., 2022) a much higher number of respondents were involved, this restriction was necessary to complete all measurements with the available equipment within the one-year time interval of interest. Nevertheless, the longitudinal design with repeated measures, combined with a robust leave-k-out validation procedure, demonstrated that the main findings are not unduly driven by a small subset of participants. This limitation, however, should be proactively addressed in future work by expanding the sample size and number of measurement devices to maintain the same level of environmental measurement accuracy.

We acknowledge that participation was limited to schools that expressed interest following initial contact, after which individual meetings were held with school administrators and information sessions were organized for parents and children to obtain the required consent. This multi-stage recruitment procedure likely introduced some degree of selection bias at both the school and family level. The participating sample consisted predominantly of children from middle-class families, with relatively low environmental noise exposure and self-reported residence in pleasant neighborhoods. It is therefore possible that the included schools and families were, on average, more motivated and environmentally and noise-conscious than the broader population. As a result, caution is warranted when generalizing the findings to more socioeconomically diverse or higher-noise exposed populations, where contextual factors and sensitivities to environmental conditions may differ.

The noise exposure indicator used in the current study is the equivalent sound pressure level. By linking the presence of the children to the rooms where they appear, a measurement equivalent to acoustic dosimetry is approached. A main advantage is that this metric is well grounded in practice with relation to the impact of noise on people, and that it reasonably converges to long term exposure levels. This does not necessarily imply that energetically equivalent levels are the most suited predictors. It has been shown e.g. that for sleep disturbance, noise events are of high relevance (see e.g. Öhström and Rylander, 1990; Janssen et al., 2014), and potentially also for attention at school, as work by Foraster et al. (2022) has yet suggested.

4.6. Public health relevance

From a broader perspective, this research contributes to the growing understanding that in an increasingly noisy world, developing adaptive strategies may play an important role in cognitive development. Although minimizing noise exposure at home and school is often considered desirable, it is possible that overly restrictive acoustic environments could reduce opportunities for children to develop resilience and coping mechanisms. However, this interpretation remains speculative and requires further empirical investigation to be substantiated.

Interestingly, this concept aligns with recent findings related to the use of noise-cancelling headphones, where excessive use may hinder the brain's ability to process common ambient sounds, potentially leading to conditions like auditory processing disorder (Whitton and Polley, 2011; Khavarghazalani et al., 2016). Although not directly related to the current work given the low scores on the hyperactivity dimension, (some) noise was shown beneficial for cognitive performance in sub-attentive children (Helps et al., 2014) or children with ADHD (Söderlund et al., 2007). Therefore, a balanced approach that includes moderate noise exposure might not necessarily be problematic, fostering adaptability and complex cognitive skills in young children.

5. Conclusions

Long-term, personalized noise measurements indicate that moderate exposure at school and at home in the evening/night may support the development of complex attentional skills, particularly divided attention, in young children making the transition from pre-school to primary school. Selective attention appears unaffected by noise and depends primarily on individual factors. While classroom indoor noise was associated with poorer performance at baseline testing, home noise at the outer façade was not; both environments contributed to a catch-up effect over the first year of elementary school. The SDQ results confirmed a behaviorally typical sample with no emotional problems and low hyperactivity, limiting generalization beyond this group.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to enhance readability, optimize text flow, and condense the writing. Only individual paragraphs were separately submitted, with explicit instructions not to alter the content or intended meaning. All AI-assisted revisions were subsequently reviewed and, where necessary, edited by the authors. The authors takes full responsibility for the final content of this publication. The illustrations in the flow diagram in Fig. 1 were generated by ChatGPT.

CRediT authorship contribution statement

Timothy Van Renterghem: Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nele De Poortere:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Pieter Thomas:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Hannah Keppler:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing. **Sarah Verhulst:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing. **Dick Botteldooren:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

References

Adler, N.E., Boyce, T., Chesney, M.A., Cohen, S., Folkman, S., Kahn, R.L., Syme, S.L., 1994. Socioeconomic status and health: the challenge of the gradient. Am. Psychol. 49 (1), 15–24.
Adler, N.E., Epel, E.S., Castellazzo, G., Ickovics, J.R., 2000. Relationship of subjective and objective social status with psychological and physiological functioning: preliminary data in healthy, white women. Health Psychol. 19 (6), 586–592.
ANSI/ASA S12.60-2010, 2010. American National Standard/Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 1: Permanent Schools. American National Standards Institute.
Anthony, L.G., Anthony, B.J., Glanville, D.N., Naiman, D.Q., Waanders, C., Shaffer, S., 2005. The relationships between parenting stress, parenting behaviour and preschoolers' social competence and behaviour problems in the classroom. Infant Child Dev. 14 (2), 133–154.
Baars, B.J., Gage, N.M., 2010. Learning and memory. In: Cognition, Brain, and Consciousness: Introduction to Cognitive Neuroscience, second ed. Academic Press, pp. 304–343.
Barrigón Morillas, J.M., Montes González, D., Rey Gozalo, G., 2016. A review of the measurement procedure of the ISO 1996 standard: relationship with the European noise directive. Sci. Total Environ. 565, 595–606.
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.
Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. Roy. Stat. Soc. B 57 (1), 289–300.
Best, J.R., Miller, P.H., 2010. A developmental perspective on executive function. Child Dev. 81 (6), 1641–1660.
Beutelmann, R., Brand, T., 2006. Prediction of speech intelligibility in spatial noise and reverberation for normal-hearing and hearing-impaired listeners. J. Acoust. Soc. Am. 120 (1), 331–342.
Bhang, S.Y., Yoon, J., Sung, J., Yoo, C., Sim, C., Lee, C., Lee, J., Lee, J., 2018. Comparing attention and cognitive function in school children across noise conditions: a quasi-experimental study. Psychiatry investigation 15 (6), 620–627.
Borghans, L., Golsteyn, B.H., Zölitz, U., 2015. School quality and the development of cognitive skills between age four and six. PLoS One 10 (7), e0129700.
Bradley, R.H., Corwyn, R.F., 2002. Socioeconomic status and child development. Annual Review of Psychology, 53 (1), 371–399.
Bryant, A., Guy, J., The CALM Team, & Holmes, J., 2020. The strengths and difficulties questionnaire predicts concurrent mental health difficulties in a transdiagnostic sample of struggling learners. Front. Psychol. 11, 587821.
Båsjö, S., Möller, C., Widén, S., Jutengren, G., Kähäri, K., 2016. Hearing thresholds, tinnitus, and headphone listening habits in nine-year-old children. Int. J. Audiol. 55 (10), 587–596.
Carter, N.L., 1996. Transportation noise, sleep, and possible after-effects. Environ. Int. 22 (1), 105–116.
Christensen, C., Koutsouris, G., Rindel, J., 2013. The ISO 3382 parameters: can we simulate them? Can we measure them?. In: Proceedings of the International Symposium on Room Acoustics, Toronto, Canada.
Cohen, S., Janicki-Deverts, D., 2012. Who's stressed? Distributions of psychological stress in the United States in probability samples from 1983, 2006, and 2009. J. Appl. Soc. Psychol. 42 (6), 1320–1334.
Demetriou, A., Spanoudis, G.C., Greiff, S., Makris, N., Panaoura, R., Kazi, S., 2022. Changing priorities in the development of cognitive competence and school learning: a general theory. Front. Psychol. 13, 954971.
Demir-Lira, Ö.E., Applebaum, L.R., Goldin-Meadow, S., Levine, S.C., 2019. Parents' early book reading to children: relation to children's later language and literacy outcomes controlling for other parent language input. Dev. Sci. 22 (3), e12764.
Dockrell, J.E., Shield, B.M., 2006. Acoustical barriers in classrooms: the impact of noise on performance in the classroom. Br. Educ. Res. J. 32 (3), 509–525.
Dzhambov, A.M., Markevych, I., Tilov, B., Arabadzhiev, Z., Stoyanov, D., Gatseva, P., Dimitrova, D.D., 2018. Pathways linking residential noise and air pollution to mental ill-health in young adults. Environ. Res. 166, 458–465.
European Parliament and Council, 2002. Directive 2002/49/EC Relating to the Assessment and Management of Environmental Noise (END).
Evans, G.W., 2006. Child development and the physical environment. Annu. Rev. Psychol. 57, 423–451.
Foraster, M., Esnaola, M., López-Vicente, M., Rivas, I., Álvarez-Pedrerol, M., Persavento, C., Sebastian-Galles, N., Pujol, J., Dadvand, P., Sunyer, J., 2022. Exposure to road traffic noise and cognitive development in schoolchildren in Barcelona, Spain: a population-based cohort study. PLoS Med. 19 (6), e1004001.
Fuggetta, G.P., 2006. Impairment of executive functions in boys with attention deficit/hyperactivity disorder. Child Neuropsychol. 12 (1), 1–21.
Gheller, F., Spicciarelli, G., Scimemi, P., Arfé, B., 2024. The effects of noise on children's cognitive performance: a systematic review. Environ. Behav.
Goodman, R., 1997. The strengths and difficulties questionnaire: a research note. JCPP (J. Child Psychol. Psychiatry) 38 (5), 581–586.
Grob, A., van Arx, P.H., Ruiter, S.A., Timmerman, M.E., Visser, L., 2018. Intelligence and Development Scales–2 (IDS-2): Intelligentie- En Ontwikkelingsschalen Voor Kinderen En Jongeren. Hogrefe.
Hall, F.L., Papakyriakou, M.J., Quirt, J.D., 1984. Comparison of outdoor microphone locations for measuring sound insulation of building facades. J. Sound Vib. 92 (4), 559–567.
Halperin, D., 2014. Environmental noise and sleep disturbances: a threat to health? Sleep Sci. 7 (4), 209–212.
Hampton Wray, A., Stevens, C., Pakulak, E., Isbell, E., Bell, T., Neville, H., 2017. Development of selective attention in preschool-age children from lower socioeconomic status backgrounds. Dev. Cogn. Neurosci. 26, 101–111.
Helps, S.K., Bamford, S., Sonuga-Barke, E.J.S., Söderlund, G.B.W., 2014. Different effects of adding white noise on cognitive performance of sub-, normal and super-attentive school children. PLoS One 9 (11), e112768.
Hindman, A.H., Connor, C.M., Jewkes, A.M., Morrison, F.J., 2008. Untangling the effects of shared book reading: multiple factors and their associations with preschool literacy outcomes. Early Child. Res. Q. 23 (3), 330–350.
Horowitz-Kraus, T., Magaliff, L., Kraus, D., Rootman, M.S., Steinberg, T., Aram, D., Radhakrishnan, R., Farah, R., 2025. Engagement of networks related to attention, executive function, and sensory processing during parental vs. experimenter story-listening: an fMRI study. Pediatr. Res.
Öhström, E., Rylander, R., 1990. Sleep disturbance by road traffic noise—A laboratory study on number of noise events. J. Sound Vib. 143 (1), 93–101.
International Organization for Standardization, 1996. ISO 9613-2: Acoustics—Attenuation of Sound During Propagation outdoors—Part 2. Geneva, Switzerland.
Janssen, S., Centen, M., Vos, H., van Kamp, I., 2014. The effect of the number of aircraft noise events on sleep quality. Applied acoustics, 84, 9–16.
Jiang, Q., Wang, D., Yang, Z., Choi, J.K., 2022. Bidirectional relationships between parenting stress and child behavior problems in multi-stressed, single-mother families: a cross-lagged panel model. Fam. Process.
Kaplan, R., Kaplan, S., 1989. The Experience of Nature: a Psychological Perspective. Cambridge University Press.
Karatekin, C., White, T., Bingham, C., 2009. Regulation of cognitive resources during an n-back task in youth-onset psychosis and attention-deficit/hyperactivity disorder (ADHD). Int. J. Psychophysiol. 73 (3), 294–307.
Kephalopoulos, S., Paviotti, M., Anfosso-Lédée, F., 2012. Common Noise Assessment Methods in Europe (CNOSSOS-EU). Publications Office of the European Union.
Khavarghazalani, B., Farahani, F., Emadi, M., Hosseini Dastgerdi, Z., 2016. Auditory processing abilities in children with chronic otitis media with effusion. Acta Otolaryngol. 136 (5), 456–459.
Kjellberg, A., 2004. Effects of reverberation time on the cognitive load in speech communication: theoretical considerations. Noise Health 7 (25), 11–21.
Klatte, M., Bergström, K., Lachmann, T., 2013. Does noise affect learning? A short review on noise effects on cognitive performance in children. Front. Psychol. 4, 578.
Klatte, M., Hellbrück, J., Seidel, J., Leistner, P., 2010. Effects of classroom acoustics on performance and well-being in elementary school children: a field study. Environ. Behav. 42 (5), 659–692.
Klenberg, L., Korkman, M., Lahti-Nuuttila, P., 2001. Differential development of attention and executive functions in 3- to 12-year-old Finnish children. Dev. Neuropsychol. 20 (1), 407–428.
Leist, L., Belke, C ., Kuhlmann, J ., Benz, S., Haba, A., Schreckenberg, D., Spilski, J., Lachmann, T., Klatte, M. (2024). The role of noise as part of neighborhood quality and its impact on well-being in German preschoolers: results from the equal-life project. Proceedings of the 53rd International Congress and Exposition on Noise Control Engineering (Internoise 2024), Nantes, France.
Lynch, J.D., Xu, Y., Yolton, K., Khoury, J.C., Chen, A., Lanphear, B.P., Cecil, K.M., Braun, J.M., Epstein, J.N., 2024. Environmental predictors of children's executive functioning development. Child Neuropsychol. 30 (4), 615–635.
Mateus, M., Carrilho, J.D., Da Silva, M.G., 2015. An experimental analysis of the correction factors adopted on environmental noise measurements performed with window-mounted microphones. Appl. Acoust. 87, 212–218.
Matheson, M., Clark, C., Martin, R., van Kempen, E., Haines, M., Lopez Barrio, I., 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, 244.
McDougal, E., Riby, D.M., Hanley, M., 2020. Profiles of academic achievement and attention in children with and without autism spectrum disorder. Res. Dev. Disabil. 104, 103689.
Mealings, K., 2021. The effect of classroom acoustic conditions on literacy outcomes for children in primary school: a review. Build. Acoust. 29 (1), 135–156.
Memoli, G., Paviotti, M., Kephalopoulos, S., Licitra, G., 2008. Testing the acoustical corrections for reflections on a facade. Appl. Acoust. 69, 479–495.

Miklós, M., Futó, J., Komáromy, D., Balázs, J., 2019. Executive function and attention performance in children with ADHD: effects of medication and comparison with typically developing children. Int. J. Environ. Res. Publ. Health 16 (20), 3822.
Mizuno, K., Tanaka, M., Fukuda, S., Imai-Matsumura, K., 2013. Divided attention of adolescents related to lifestyles and academic and family conditions. Brain Dev. 35 (5), 435–440.
Morales-Muñoz, I., Nolvi, S., Mäkelä, T., et al., 2021. Sleep during infancy, inhibitory control and working memory in toddlers: findings from the FinnBrain cohort study. Sleep Sci. Pract 5, 13.
Munakata, Y., Michaelson, L., Barker, J., Chevalier, N., 2013. Executive functioning during infancy and childhood. In: Tremblay, R.E., Boivin, M., Peters, R. DeV. (Eds.), Encyclopedia on Early Childhood Development [Online]. Centre of Excellence for Early Childhood Development. https://www.child-encyclopedia.com/executive-functions/according-experts/executive-functioning-during-infancy-and-childhood.
Noble, K.G., McCandliss, B.D., Farah, M.J., 2007. Socioeconomic gradients predict individual differences in neurocognitive abilities. Dev. Sci. 10 (4), 464–480.
Ntousi, I., Gonida, E.N., Kioseoglou, G., 2019. Children's cognitive and metacognitive performance during early childhood: rate of growth and individual differences. Psychology: J. Hellenic Psycholo. Soc. 24 (1), 157–176.
Persson Waye, K., Löve, J., Lercher, P., Dzhambov, A., Klatte, M., Schreckenberg, D., Belke, C., Leist, L., Ristovska, G., Jeram, S., et al., 2023. Adopting a child perspective for exposome research on mental health and cognitive development - conceptualisation and opportunities. Environ. Res. 239, 117279.
Pineda, R.C., Krampe, R.T., Vanlandewijck, Y., Van Biesen, D., 2023. Scoping review of dual-task interference in individuals with intellectual disability. Front. Psychol. 14, 1223288.
Pirrera, S., De Valck, E., Cluydts, R., 2010. Nocturnal road traffic noise: a review on its assessment and consequences on sleep and health. Environ. Int. 36 (5), 492–498.
Pujol, S., Levain, J.-P., Houot, H., Petit, R., Berthillier, M., Defrance, J., Lardies, J., Masselot, C., Mauny, F., 2014. Association between ambient noise exposure and school performance of children living in an urban area: a cross-sectional population-based study. J. Urban Health 91, 256–271.
Reynaud, E., Vecchierini, M.-F., Heude, B., Charles, M.-A., Plancoulaine, S., 2019. Sleep and Its Relation to Cognition and Behaviour in preschool-aged Children of the General Population: a Systematic Review arXiv Preprint.
Sato, H., Bradley, J.S., 2008. Evaluation of acoustical conditions for speech communication in working elementary school classrooms. J. Acoust. Soc. Am. 123 (4), 2064–2077.
Söderlund, G., Sikström, S., Smart, A., 2007. Listen to the noise: Noise is beneficial for cognitive performance in ADHD. JCPP (J. Child Psychol. Psychiatry) 48, 840–847.
Shield, B.M., Dockrell, J.E., 2008. The effects of environmental and classroom noise on the academic attainments of primary school children. J. Acoust. Soc. Am. 123, 133–144.
Stansfeld, S.A., Berglund, B., Clark, C., Lopez-Barrio, I., Fischer, P., Öhrström, E., et al., 2005. Aircraft and road traffic noise and children's cognition and health: a cross-national study. Lancet 365 (9475), 1942–1949.
Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A., Zelson, M., 1991. Stress recovery during exposure to natural and urban environments. J. Environ. Psychol. 11 (3), 201–230.
Valente, D.L., Plevinsky, H.M., Franco, J.M., Heinrichs-Graham, E.C., Lewis, D.E., 2012. Experimental investigation of the effects of the acoustical conditions in a simulated classroom on speech recognition and learning in children. J. Acoust. Soc. Am. 131 (1), 232–246.
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), 25.
Van Renterghem, T., 2019. Towards explaining the positive effect of vegetation on the perception of environmental noise. Urban For. Urban Green. 40, 133–144.
Van Renterghem, T., Botteldooren, D., Dekoninck, L., 2012. Evolution of building facade road traffic noise levels in flanders. J. Environ. Monit. 14 (3), 677–686.
Van Renterghem, T., Thomas, P., Dominguez, F., Dauwe, S., Touhafi, A., Dhoedt, B., Botteldooren, D., 2011. On the ability of consumer electronics microphones for environmental noise monitoring. J. Environ. Monit. 13 (3), 544–552.
Van Renterghem, T., Botteldooren, D., 2010. The importance of roof shape for road traffic noise shielding in the urban environment. J. Sound Vib. 329 (9), 1422–1434.
Vugteveen, J., de Bildt, A., Timmerman, M.E., 2022. Normative data for the self-reported and parent-reported strengths and difficulties questionnaire (SDQ) for ages 12–17. Child Adolesc. Psychiatr. Ment. Health 16 (1), 5.
Weighall, A., Kellar, I., 2023. Sleep and memory consolidation in healthy, neurotypical children and adults: a summary of systematic reviews and meta-analyses. Emerg. Top. Life Sci. 7 (5), 513–524.
Whitton, J.P., Polley, D.B., 2011. Evaluating the perceptual and pathophysiological consequences of auditory deprivation in early postnatal life: a comparison of basic and clinical studies. J. Asso. Res. Otolaryngolo. 12 (4), 535–547.