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Association between community noise and children's cognitive and behavioral development: A prospective cohort study

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ABSTRACT

Background: Noise exposure has been associated with adverse cognitive and behavioral outcomes in children, but evidence on longitudinal associations between community noise and child development in low- and middle-income countries is rare. We investigated associations between community noise and behavioral and cognitive development in preschool children in São Paulo.
Methods: We linked child development data from the São Paulo Western Region Birth Cohort with average (Lden) and night-time (Lnight) community noise exposure at children's home, estimated by means of a land use regression model using various predictors (roads, schools, greenness, residential and informal settlements). Outcomes were the Strengths and Difficulties Questionnaire (SDQ) and Regional Project on Child Development Indicators (PRIDI) at 3 years of age and the Child Behavior Checklist (CBCL) and International Development and Early Learning Assessment (IDELA) at 6 years of age. We investigated the relationship between noise exposure and development using cross-sectional and longitudinal regression models.
Results: Data from 3385 children at 3 years of age and 1546 children at 6 years of age were analysed. Mean Lden and Lnight levels were 70.3 dB and 61.2 dB, respectively. In cross-sectional analyses a 10 dB increase of Lden above 70 dB was associated with a 32% increase in the odds of borderline or abnormal SDQ total difficulties score (OR = 1.32, 95% CI: 1.04; 1.68) and 0.72 standard deviation (SD) increase in the CBCL total problems z-score (95% CI: 0.55; 0.88). No cross-sectional association was found for cognitive development. In longitudinal analyses, each 10 dB increase was associated with a 0.52 SD increase in behavioral problems (95% CI: 0.28; 0.77) and a 0.27 SD decrease in cognition (95%-CI: 0.55; 0.00). Results for Lnight above 60 dB were similar.
Discussion: Our findings suggest that community noise exposure above Lden of 70 dB and Lnight of 60 dB may impair behavioral and cognitive development of preschool children.

1. Introduction

Noise exposure is increasingly recognized as an important public health issue. The European Environmental Agency (EEA) estimates that 22 million people suffer chronic high annoyance, 6.5 million people suffer chronic high sleep disturbance and that 12,000 premature deaths occur due to long-term exposure to community noise, annually (European Environment Agency, 2020). Even though the WHO identified noise pollution as a major public health threat in low- and middle-income countries (LMICs) (Berglund et al., 1999), evidence on the impact of noise in LMICs remains extremely limited. Community noise exposure is currently not even mentioned in the Global Burden of Disease project (GBD Collaborators, 2019).

Most of the existing noise literature focuses on adult health in general, and cardiovascular disease in particular (van Kempen et al., 2018). Much less is known for children, who may be more vulnerable to noise due to their more limited capacity to anticipate and cope with stress (Stansfeld et al., 2005). The best currently available evidence for children has focused on the effect of aircraft noise exposure on reading and memory skills (Haines et al., 2001a; Haines et al., 2001b; Hygge et al., 2002; Lercher et al., 2003; Stansfeld et al., 2005). The EEA estimates that 12,500 schoolchildren suffer learning impairment in school from

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aircraft noise (European Environment Agency, 2020). Community noise may also affect mental health of children resulting in behavioral problems, although evidence is inconsistent (Clark and Paunovic, 2018b; Haines et al., 2001a; Stansfeld et al., 2005; Zare Sakhvidi et al., 2018; Zijlema et al., 2021). For instance, the Road Traffic and Aircraft Noise Exposure and Children's Cognition and Health (RANCH) study found no association between noise exposure to aircraft or road traffic at school and children's mental health in three large European airports (Stansfeld et al., 2005), whereas Evans et al reported that airport noise led to reduced mental health in children (Evans et al., 1995). The latter finding is supported by the study of Hjortebjerg et al (2016). They document an increased incidence of behavioral problems, particularly hyperactivity and inattention symptoms, in children exposed to residential road traffic (Hjortebjerg et al., 2016), in line with the findings of a recent review on road traffic noise (Schubert et al., 2019).

In adults, health consequences are considered to be related to the distress produced by increased physiological arousal because of recurrent stimulation of the endocrine system and autonomic nervous system (Babisch, 2002). This could also be true for children since elevated levels of adrenaline and noradrenaline were found in two studies examining aircraft noise exposure in children (Evans et al., 1998; Evans et al., 1995). Further, night-time noise is expected to affect sleep duration and quality (Basner and McGuire, 2018) as recently observed for children in the first year of life (Blume et al., 2021). Chronic distress and insufficient sleep are well established risk factors for mental health including behavioral problems, motivation for learning and cognitive impairments (McEwen, 2006).

Most of the currently available literature focuses on older, school-attending children exposed to major noise sources like airports or road traffic at school, but does not consider a broader set of residential community noise sources such as local exposure to industry or outdoor nightlife. Additionally, many studies were conducted only for noise exposure at school. However, noise exposure at children's home might also be relevant, in addition to school, since children spend more time at home and may be adversely impacted in several activities such as communication, homework, rest and sleep.

Furthermore, longitudinal evidence is rare and it is unknown if prolonged exposure to noise leads to increased, constant or even lessen effects due to adaptation. Haines et al provided evidence that the effect of noise exposure on child cognition do not habituate within one year (Haines et al., 2001c). Clark et al found a weak longitudinal association between aircraft noise and poorer reading and no longitudinal association between aircraft noise and behavioral problems (SDQ) (Clark et al., 2013).

Noise effects may not only be influenced by physical parameters but also by the cultural context, the house insulation and personal factors including noise sensitivity and knowledge about environmental health risks (Okokon et al., 2015). The study of Gjestland et al. demonstrated more tolerance to road traffic noise in Vietnamese people compared to European and North America, but similar annoyance to aircraft noise (Gjestland et al., 2015). In South Africa a higher percentage of noise sensitive and annoyed individuals were found compared to Switzerland (Sieber et al., 2018). A study in São Paulo assessed noise-related annoyance in adults which showed high results of 48.4% annoyed people, indicating high noise exposure being a problem in this area (Paiva et al., 2019).

The present study aimed to investigate the effect of noise exposure on cognitive and behavioral development in three to six year old children in São Paulo, considering various sources of community noise and using a longitudinal design.

2. Methods

2.1. Study population

The study is based on the São Paulo Western Region Birth Cohort (SP-ROC). Details about the SP-ROC cohort and the recruitment of participants have been published previously (Brentani et al., 2020). In brief, the cohort was launched in 2012 as a longitudinal study to examine the relationship between early life risk exposure and long-term outcomes in a modern and predominantly poor urban context. The SP-ROC cohort comprises of all children from the Butantã/Jaguaré region born at São Paulo's University Hospital (HU USP) between April 1, 2012 and March 31, 2014. A total of 6162 children were included in the cohort with informed consent from caregivers. Electronic medical records from the university hospital were used to extract information on birth and other clinical data. During postpartum period, mothers completed questionnaires on socio-economic status and family background. At the child's age of 3 and 6 years, assessments on child development and parental lifestyle were performed at children's homes.

2.2. Noise exposure assessment

Noise exposure assessment and modeling has been previously described in detail and published (Raess et al., 2021). Weekly measurements of A-weighted equivalent sound pressure levels (LAeq) averaged at 1-s intervals were performed once or twice over one week at 42 homes sites from 12 and 19 February 2019 (summer season) and from 7 to 14 August 2019 (winter season). A Type-II Sound Level Meter Data Logger Noise Sentry RT (Convergence Instruments, Sherbrooke, QC, Canada) was installed outside each location. Lden was calculated with a 5 dB penalty for the evening measurements (18:00–23:00) and a 10 dB penalty for the night measurements (23:00–07:00). Based on these measurements and relevant geographic information system (GIS) predictive variables, a land use regression (LUR) model was developed to estimate Lden and Lnight (23:00–07:00) at residential addresses of all study participants. The five predictive GIS variables (proportion of educational facilities within a 400 m buffer, inverse distance to the closest medium road (including motorway, trunk, primary, secondary and tertiary roads), proportion of informal settlements ("favelas") within a 400 m buffer, proportion of residential land use within a 50 m buffer (Lden) and 25 m buffer (Lnight) and mean Normalized Difference Vegetation Index (NDVI) indicating the greenness of an area within a 100 m buffer) explained 56% (Lden) respectively 63% (Lnight) of the observed variance in the average noise measurements. We used this model for predicting long-term noise exposure at all household locations of children included in the study. Unrealistic high noise values due to model parameter extrapolation were censored, i.e. set to 80 dB for Lden and 75 dB for Lnight (Fig. 1).

2.3. Cognitive and behavioral outcomes

Behavioral problems at 3 years of age were assessed by the parent-reported Strength and Difficulties Questionnaire (SDQ), which is a standard behavioral screening questionnaire for children (Goodman, 1997) previously validated in Brazil (Cury and Golfeto, 2003; Fleitlich et al., 2000; Goodman et al., 2012). The questionnaire includes 25 items with five subscales: emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems, and prosocial behavior. Each subscale consists of five items answered on a scale of "not true" (0), "somewhat true" (1), or "certainly true" (2). These ratings are summed up for the subscale score. The total difficulties score is generated by summing up all subscale scores except the prosocial behavior, which was not considered for our analyses (YouthinMind, 2021). Therefore, a higher total difficulty and subscale scores indicates more behavioral problems. The total difficulties score was divided into 3 categories based on cutoff points: normal, borderline and abnormal. The cutoff levels for Brazilian children are as follows: 0–13 for the normal category, 14–16 for the borderline category, and 17–40 for the abnormal category (Fleitlich et al., 2000). Only children with no missing values on the items were included (3358 out of 3385 children).

Behavioral problems at 6 years of age were assessed by the parent-

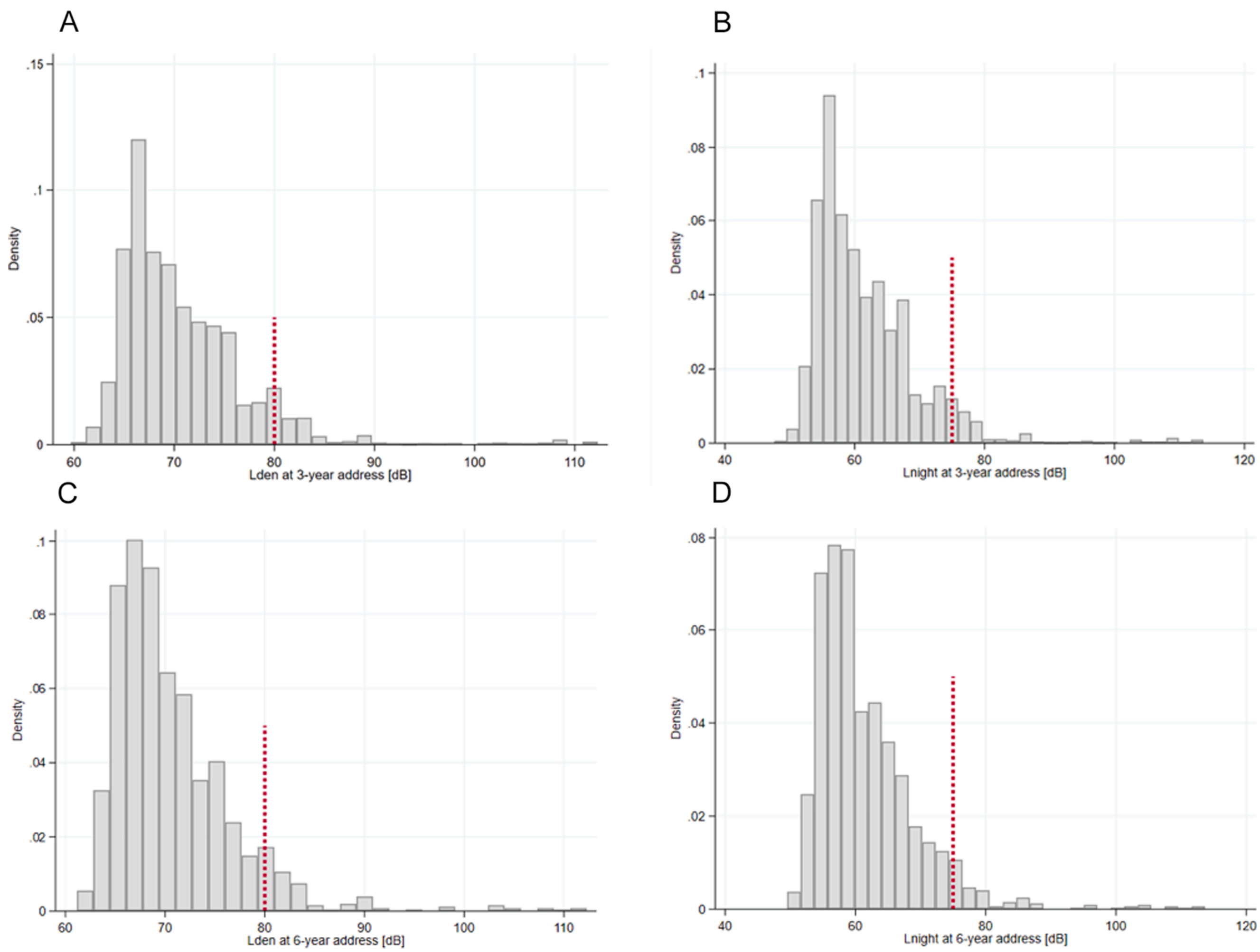

Fig. 1. Summary statistics of predicted noise according to a land use regression (LUR) model in dB for children within study area (Butantã/Jaguaré region in São Paulo). A: Lden at 3-year address (n = 3385); B: Lnight at 3-year address (n = 3385); C: Lden at 6-year address (n = 1546); D: Lnight at 6-year address (n = 1546). High predicted noise values were censored at 80 dB for Lden and 75 dB for Lnight (red-dotted line) for epidemiological analysis. Note: Lden (00:00–24:00), 5 dB penalty for the evening measurements (18:00–23:00) and 10 dB penalty for the night measurements (23:00–07:00). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reported Child Behavior Checklist (CBCL) (Achenbach, 1991). The reliability and validity of the CBCL as behavioral screening tool have been well documented internationally as well as in Brazil (Heubeck, 2000; Rocha et al., 2013). The checklist includes 120 items which describe behavior in the past 6 months. Assessment is done on a 3-point scale (0–2 points), with higher scores indicating more behavioral problems. The checklist is divided into 8 syndrome scale scores (Anxious/Depressed, Withdrawn/Depressed, Somatic Complaints, Social Problems, Thought Problems, Attention Problems, Rule-Breaking Behavior and Aggressive Behavior) as well as broadband scales which reflect the sum of these subscales (Internalizing Problems: summary of Anxious/Depressed, Withdrawn/Depressed, and Somatic Complaints scores. Externalizing Problems: summary of Rule-Breaking Behavior and Aggressive Behavior scores. Total problems score: summary of all 8 syndrome scale scores, representing overall behavioral problems). Z-scores were calculated for the total problems score as well as the subscales, using mean and standard deviation. Only children with no missing values on the items were included (1488 out of 1546 children).

For assessment of cognitive development at age of three years, the Regional Project on Child Development Indicators (PRIDI) was used, which is a direct observation tool developed specifically for Latin America (Verdisco et al., 2016). The assessment includes 21 items for capturing four domains: cognition, communication and language, socioemotional, and motor. Achieved scores, a higher score represents a better result, were transformed into z-scores using mean and standard deviation. Only children with no missing values on the items were included (2930 out of 3385 children).

Cognitive development at 6 years of age was assessed by the International Development and Early Learning Assessment (IDELA) (Pisani et al., 2018), which aims to measure five distinct domains of child development: Emergent Literacy, Emergent Numeracy, Executive function, Social-Emotional Skills, and Gross and Fine Motor Skills. It contains 22 items, with higher score numbers denoting better performance on the item. Achievement is expressed as percentage. Only children with no missing values on the items were included (1490 out of 1546 children).

2.4. *Definition of covariates*

We investigated basic characteristics of the children that may affect children's development and could possibly be linked with noise exposure, including age at assessment day, gender, low birthweight at birth (higher or lower than 2500 g), prematurity (before or after 38 gestational weeks according to Capurro score), small for gestational age (below 10th percentile according to Intergrowth-21st curves), APGAR score 5 min after birth (normal or below 10 points) and the disability status of the child, reported by the caregiver (however, children with hearing or mental disabilities were previously excluded from analyses). To adjust for socioeconomic factors, we considered parental educational level (no, elementary, middle and upper grade), marital status of caregiver (single, separated or widow versus married or live together versus other), mother's age at birth, monthly household income (quantiles for 3-year analysis, Socioeconomic Status Brazilian classification from A (higher) to E (lower) for 6-y analysis (Baeninger and Jannuzzi, 1996)), financial support, the caregivers' skin-color (white, mixed, black) and household size were included. Additionally, we also assessed children's exposure to stimulating activities at home using the short version of the HOME questionnaire used in the Multiple Indicator Cluster Survey (MICS) program (UNICEF, 2006). The MICS stimulation score ranges from 0 (no engagement in any stimulation activity, e.g. reading books, playing with child) to 6 (caregiver engagement in all stimulation activities within the last 3 days), and has been linked to improved cognitive and socioemotional development in previous research (Jeong et al., 2016).

Depression status was assessed in the 3-year follow-up using the Edinburgh Score (Cox et al., 1987) (no: 0–10 points, possibly: 11–13 points, likely: > 13 points) and in the 6-year follow-up using the CESD-10 score (Andresen et al., 1994) (no: 0–15, mild: 16–20, moderate: 21–25, severe: > 25). For assessing parental stress, the Abidin's Parenting Stress Index (PSI), a standard measure of perceived stress in the caregiving role related to child rearing, was used and is reflected on a scale from 0 to 32, with higher values representing more stress (Abidin, 1995).

Data of covariates were available from child and parent questionnaires and hospital reports at baseline and 3-year and 6-year follow-up.

2.5. Statistical analysis

Descriptive analyses were performed to analyze the study sample concerning demographic characteristics, socioeconomic and other variables which might affect the cognitive and behavioral development of the child and are possibly linked with noise exposure. For comparison of distributions changes of these variables in the different study populations at birth and after 3 and 6 years due to attrition, chi-squared test was performed for categorical variables and classical *t*-test for continuous variables.

Multiple imputation was used to address missing covariate data (Sterne et al., 2009). In the 3-year assessment, 5 out of 17 covariates showed complete data. Of the 12 covariates with missing data, 8 had missing data below 5%. Only information on income and parental stress showed high amounts of missing data with 17%, respectively 34%. In the 6-year assessment, 4 out of 16 covariates showed complete data. Covariates with missing data had no more than 5% of missing values. Only 47% of children in the 3-year sample and 88% of children in the 6-year sample would have been available for analysis under the traditional listwise deletion method. We used the Stata "mi impute chained" command. All exposure, outcome and confounding variables of children included in the study were used in the imputation equations and 5 cycles of the imputation were run. Imputed values compared reasonably to observed values, therefore only results with included imputed values are presented for the following analyses.

We conducted non-parametric exposure–response analysis to inform the modelling strategy using a local polynomial smooth plot. Based on visual inspections of these analysis we decided to model a linear noise-response relationship above 70 dB for Lden and 60 dB for Lnight.

With respect to noise exposure univariate and multivariable analyses were conducted, applying ordered logistic regression for ordinal outcomes (SDQ categories) and linear regression for continuous outcomes (CBCL, PRIDI and IDELA and its subcategories and SDQ raw scores). We conducted cross-sectional and longitudinal analysis. For the latter, z-scores were additionally calculated for SDQ total difficulties scores and IDELA score using mean and standard deviation for enabling comparison of SDQ and CBCL as well as PRIDI and IDELA. The differences of z-scores of behavioral and cognitive assessments at six years minus three years of age were calculated and analyzed in a multivariable linear regression in relation to noise exposure. For noise exposure, the address at 6 years of age was chosen for the non-movers, which is identical with the address at 3 years of age. For the movers, analysis was done for both noise exposures, at the 3-years and the 6-years address, since the date of movement was unclear. The residuals were checked for normal distribution, homoscedasticity and influential points.

We conducted several sensitivity analyses. First, in an extended sensitivity analysis, caregiver's depression and parental stress status were included as additional confounding variables. These factors are known to be negatively associated with child's cognitive and behavioral development (Barroso et al., 2018; Goodman et al., 2011). Second, all main analyses were repeated while excluding those participants who had moved since birth for the 3-year analysis and moved since the 3-assessment for the 6-year analysis. Third, in order to evaluate potential residual confounding, a sensitivity analysis was performed excluding children living in the largest informal settlement (Paraisópolis), an area with the lowest socioeconomic status and highest predicted noise values.

For all tests, statistical significance was set at $p < 0.05$ (two-tailed).

All statistical analyses were performed using STATA statistical software (Version 16.1) (STATA Corp LP, College Station, Texas).

3. Results

3.1. Study population description

The 3-year assessment was completed by 3619 children and their caregivers. Ninety children were excluded because of incomplete home address at birth or follow-up, 132 children were excluded because they lived outside of the study area where the LUR noise model was applicable and 12 children because of mental disability or severe hearing problems. The 6-year assessment was completed by a smaller sample of 1849 children as field work had to be discontinued in the face of COVID-19 restrictions in Brazil. Out of 1849 caregiver and children interviewed, 163 had to be excluded due to missing or incorrect home addresses, 138 children living outside of the study area and 2 because of disabilities. In the end, 3385 children were included from the 3-year assessment and 1546 from the 6-year assessment (Fig. 2). Characteristics of the study population are summarized in Table 1. No substantial differences of socio-demographic factors and noise exposure were seen between the 3- and 6- year study samples (Supplementary Table S1). Except, some small but significant differences were observed for the mother's age at birth, the APGAR score, birthweight and term births, all with higher values in the follow-up populations.

In Supplementary Table S2, summary statistics of the assessments of behavioral problems (SDQ total difficulties score and the CBCL total problems z-score) and cognitive development (PRIDI z-score and IDELA) are presented. Based on the SDQ total difficulties score, 2543 children (76%) were classified as normal, 343 children (10%) as borderline and 472 children (14%) as abnormal.

3.2. Noise levels

Fig. 1 as well as Supplementary Table S3 summarize predicted noise levels at children's home addresses. Mean Lden and Lnight was the same for 3-year and 6-year addresses with 70.3 dB and 61.2 dB, respectively. Pearson and Spearman correlation between Lden and Lnight were high (between 0.994 and 0.997). For 3-year addresses, 7.3% of Lden values and 6.8% for 6-year addresses were above 80 dB. For Lnight, 5.6% of values for 3-year addresses and 5.2% for 6-year addresses were above 75 dB. Minimal values were 60 dB for Lden and 48 dB for Lnight. Fig. 3 demonstrates that high noise levels were mostly found around larger roads, informal settlements and educational facilities, mainly in Paraisópolis in the South-east of the study area, where 383 (11%) respectively 169 (11%) of children lived during the 3-year and 6-year assessment.

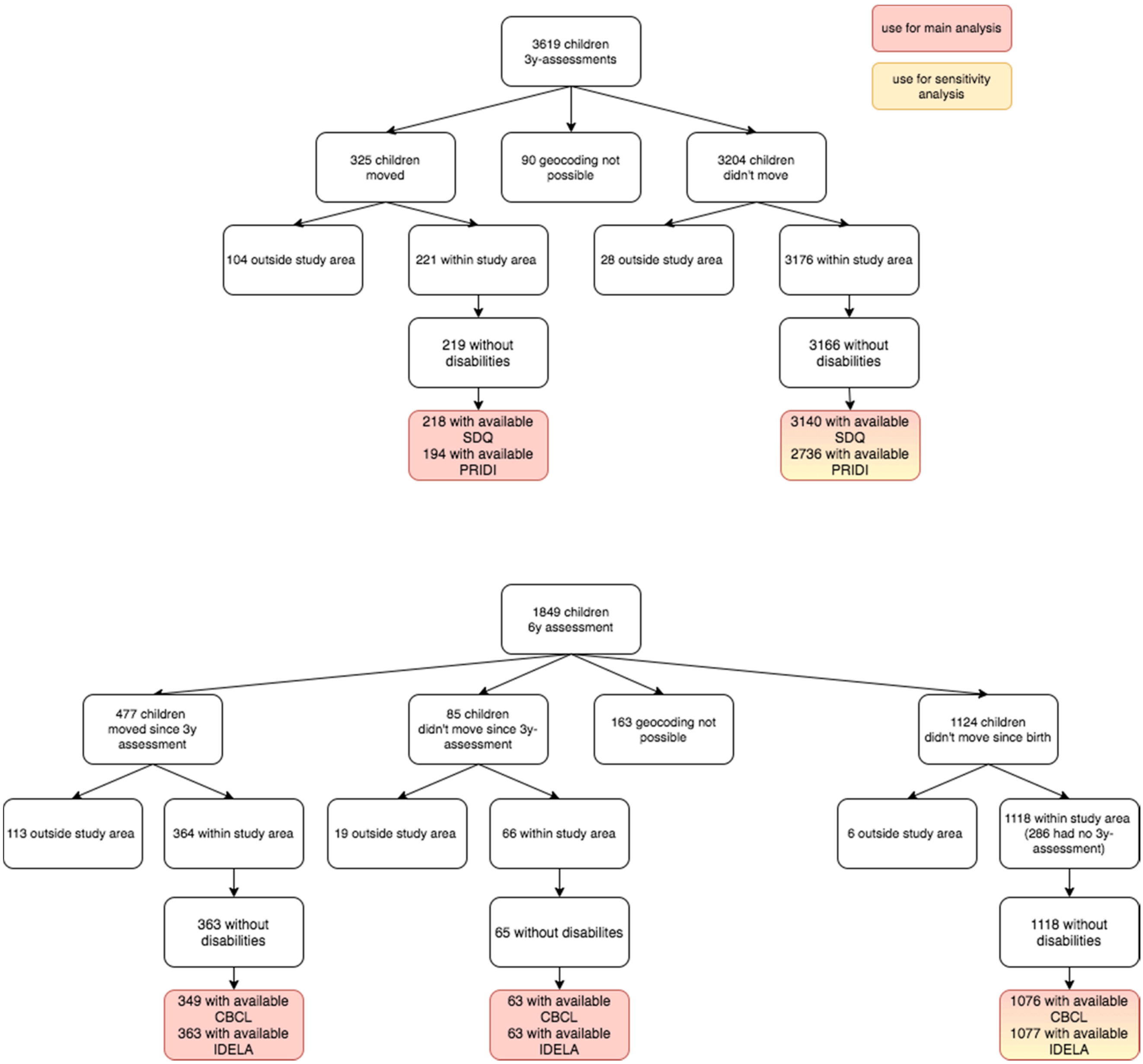

Fig. 2. Overview of study population, including and excluding factors as well as completed assessments and allocation for statistical analyses.

Fig. 4 shows the non-parametric relationship between community noise exposure and children's developmental outcome. We found a roughly linear monotonic exposure–response relationship above 70 dB for Lden and 60 dB with minor (close to zero) slopes below these values. Therefore, noise exposure was analyzed continuously above these thresholds, and values below these thresholds were set to 70 dB and 60 dB, respectively.

3.3. *Cross-sectional association of child development and community noise exposure*

Table 2 shows the results of the unadjusted and adjusted ordinal logistic regression of the association between community noise exposure at home and children's behavioral problems measured by the SDQ total difficulties score categories at 3 years of age as well as an unadjusted and adjusted linear regression for raw scores of SDQ subcategories. Additionally, unadjusted and adjusted linear regression results for CBCL total problems and subcategories z-scores at 6 years of age. At 3 years of age, we observed that higher noise levels were associated with 32% increase in the odds of a borderline or abnormal SDQ total difficulties score (aOR 1.32, 95% CI: 1.04;1.68) per 10 dB increase of Lden and a 24% increase for Lnight (aOR 1.24, 95% CI: 1.05;1.46). Looking at the subcategories, the strongest association with community noise exposure was found for emotional problems with an adjusted mean score increase of 0.37 (95% CI: 0.16, 0.59) per 10 dB Lden and for hyperactivity with a mean score increase of 0.34 (95% CI: 0.08, 0.60) per 10 dB Lden. The associations for conduct problems and peer relationship problems were of similar magnitude but had slightly larger confidence intervals. At 6 years of age, each 10 dB increase of Lden was associated with an 0.72 SD increase in the CBCL total problems z-score (95% CI: 0.55, 0.88), with similar effect sizes for night exposure (Coef = 0.52, 95% CI: 0.40, 0.63). The strongest associations with CBCL subcategories were found for social problems (Coef = 0.73, 95% CI: 0.55; 0.91), anxiety/depression problems (Coef = 0.69, 95% CI: 0.52; 0.86), internalizing (Coef = 0.69, 95% CI: 0.52;0.86) and attention problems (Coef = 0.63, 95% CI: 0.46; 0.81).

Table 3 summarizes the results for cognitive development. No cross-sectional associations were found between community noise exposure and cognitive development at 3 years (PRIDI z-score, Coef = 0.08, 95%

Table 1
Characteristics of São Paulo Western Region Birth Cohort (SP-ROC) at 3-year (n = 3385) and 6-year assessment (n = 1546).

	3 years			6 years		
characteristics	n	n / mean	% / SD	n	n / mean	% / SD
Age (months) [a]	3385	40.9	7.2	1480	75.7	5.0
Gender	3385			1546		
male		1666	49.2%		793	51.3%
female		1719	50.8%		753	48.7%
Birthweight	3385			1546		
normal (≥2500 g)		3180	93.9%		1447	93.6%
low (<2500 g)		205	6.1%		99	6.4%
Small for gestational age	3271			1490		
no		3008	92.0%		1375	92.3%
yes (<10 percentile)		263	8.0%		115	7.7%
Premature	3381			1545		
no		2659	90.4%		1217	90.9%
yes (<37 weeks)		722	9.6%		328	9.1%
APGAR 5 min	3385			1546		
normal		2605	77.0%		1149	74.3%
low (<10)		780	23.0%		397	25.7%
Disabilities[a]	3331			1462		
no		3218	96.6%		1297	88.7%
yes		113	3.4%		165	11.3%
Age of mother at birth	3385	26.0	6.4	1546	26.3	6.5
Caregiver's skin-color	3381			1545		
white		2038	60.3%		904	58.5%
mixed		143	4.2%		575	37.2%
black		1200	35.5%		66	4.3%
Marital status of caregiver[a]	3342			1481		
single, separated, widow		1229	36.8%		55	34.8%
married, live together		1508	45.1%		956	65.5%
other		605	18.1%		10	0.7%
Education grade of caregiver[a]	3248			1483		
none		121	3.7%		32	2.1%
elementary		1322	40.7%		437	29.5%
middle		1630	50.2%		866	58.4%
upper		175	5.4%		148	10.0%
Income of caregiver[a] ([b]/[c])	2797			1487		
1. quantile (0–1000 USD) / A		767	27.4%		6	0.4%
2. quantile (1020–1600 USD) / B1		686	24.5%		22	1.5%
3. quantile (1680–2200 USD) / B2		663	23.7%		130	8.7%
4. quantile (2240–12000 USD) / C1		681	24.4%		451	30.3%
- / C2					666	44.8%
- / D & E					212	14.3%
Financial support[a]	3242			1463		
no		2352	72.6%		1091	74.6%
yes		890	27.4%		372	25.4%
Household size[a]	3357	4.3	1.4%	1484	4.4	1.5%
Parental stress score[d]	2236	14.8	6.1%			
Depression[a] ([b]/[c])	3110			1490		
no / no		2339	75.2%		1091	73.2%
possible / mild		438	14.1%		123	8.3%
likely / moderate		333	10.7%		102	6.9%
- / severe					174	11.7%
MICS stimulation score[a]	3360.0	5.0	1.4%	1488	4.3	1.7%

Note: MICS, Multiple Indicator Cluster Survey
[a] repeatedly assessed at 3 years and 6 years (not same values)
[b] classification for 3-year assessment
[c] classification for 6-year assessment
[d] only assessed at 3-year assessment

CI: −0.04, 0.19) and 6 years (IDELA percent, Coef = -0.49, 95% CI: 2.71, 1.74) of age.

3.4. Longitudinal associations between community noise exposure and cognition and behavior problems

Table 4 summarizes the results of our longitudinal analysis. On average, each 10 dB increase Lden noise exposure was associated with a 0.52 SD deviation increase in behavioral problems 0.52 (95%-CI: 0.28, 0.77), and an 0.27 SD decline in cognitive scores (95%-CI: 0.55, 0.00) between ages three and six.

4. Sensitivity analysis

Results of various sensitivity analysis are summarized in Tables 4 and 5. Restricting the longitudinal analyses to children who did not move between the 3-year and 6-year assessment showed stronger associations with community noise exposure, particularly for cognitive performance, compared to the whole and the moved sample (Table 4). This analysis was done for both noise exposures in the moved sample, at the 3-year and the 6-year address, since it is unclear when the children moved during this period of 3 years and which noise exposure time window would be more relevant.

In the cross-sectional analyses, excluding movers had little impact on

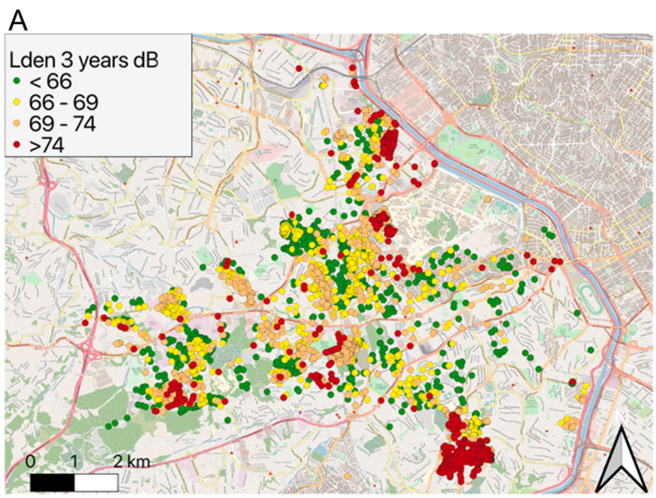

Fig. 3. Map of study area (Butantã/Jaguaré region in São Paulo) with predicted noise according to a land use regression (LUR) model in dB. Each dot represents the Lden value (Figure A) and Lnight value (Figure B) for a child (n = 3385). Color gradation representing quantiles. Note: Lden (00:00–24:00), 5 dB penalty for the evening measurements (18:00–23:00) and 10 dB penalty for the night measurements (23:00–07:00).

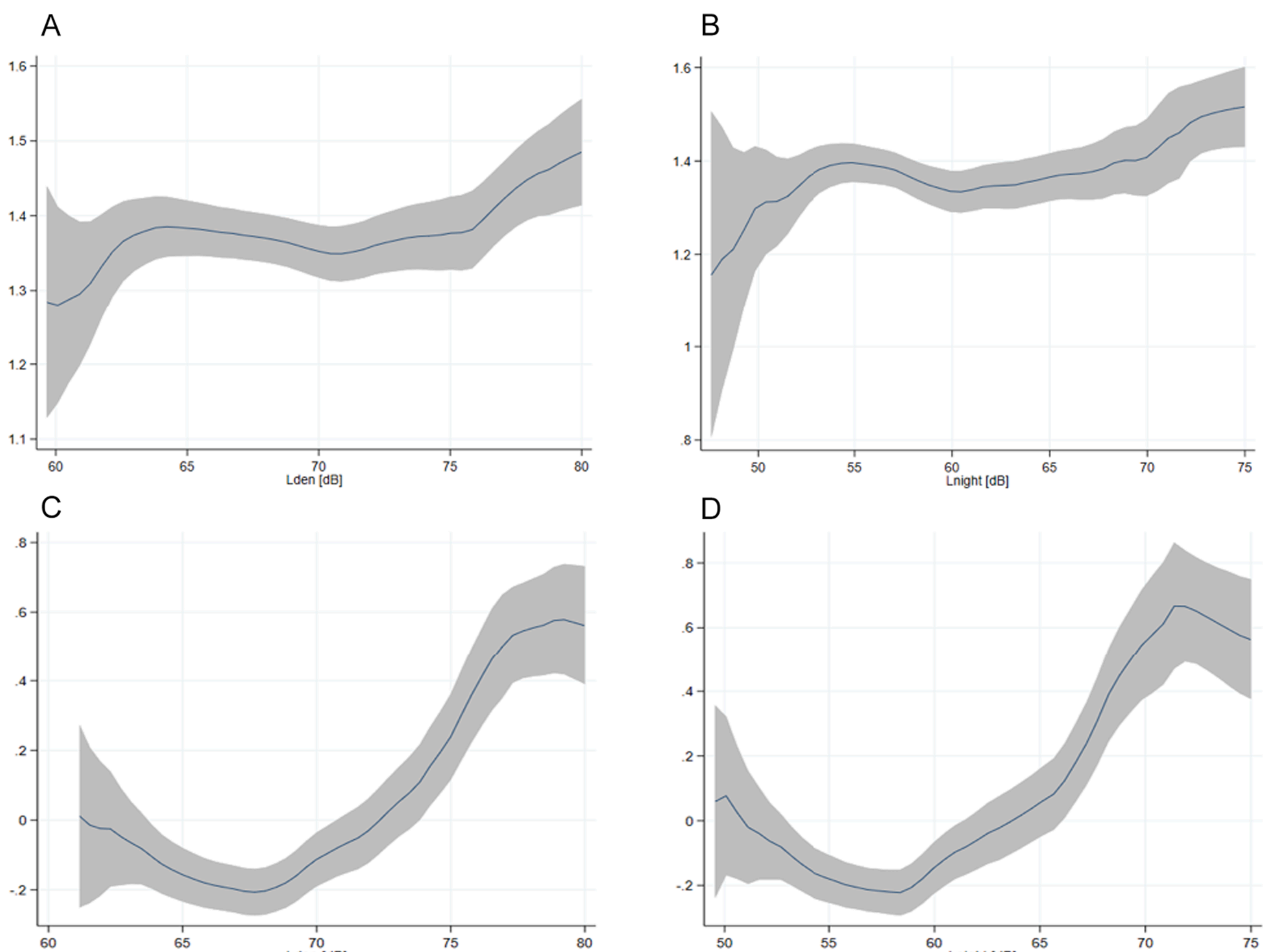

Fig. 4. Non-parametric plot analyzing the linearity of the cross-sectional relationship between community noise exposure and children's behavioral development. A: Lden and SDQ (n = 3358); B: Lnight and SDQ (n = 3358); C: Lden and CBCL (n = 1489); D: Lnight and CBCL (n = 1489). Note: Lden (00:00–24:00), 5 dB penalty for the evening measurements (18:00–23:00) and 10 dB penalty for the night measurements (23:00–07:00); SDQ, Strengths and Difficulties Questionnaire; CBCL, Child Behavior Checklist.

Table 2
Association between a 10 dB increase in community noise exposure (Lden and Lnight) and behavioral development assessed by the SDQ in 3-year old children (n = 3358) and by CBCL in 6-year old children (n = 1489) using ordinal logistic or linear regression analysis.

	Lden				Lnight			
Assessment	Unadjusted per 10 dB	*p*-value	adjusted[c] per 10 dB	*p*-value	unadjusted dB	*p*-value	adjusted[c] per dB	*p*-value
SDQ (per category)	**OR[a] [95% CI]**		**OR[a] [95% CI]**		**OR[a] [95% CI]**		**OR[a] [95% CI]**	
Total difficulties score	1.46 [1.16; 1.83]	0.001	1.32 [1.04;1.68]	0.021	1.32 [1.13;1.55]	0.001	1.24 [1.05;1.46]	0.012
SDQ (raw scores)	**Coef.[b] [95% CI]**		**Coef.[b] [95% CI]**		**Coef.[b] [95% CI]**		**Coef.[b] [95% CI]**	
Total difficulties score	1.41 [0.78;2.04]	<0.001	1.08 [0.43;1.73]	<0.001	1.04 [0.61;1.48]	<0.001	0.81 [0.35;1.26]	<0.001
Emotional	0.40 [0.19;0.62]	<0.001	0.37 [0.16;0.59]	<0.001	0.30 [0.15;0.45]	<0.001	0.27 [0.12;0.42]	<0.001
Conduct	0.35 [0.09;0.06]	0.008	0.24 [-0.01;0.50]	0.064	0.26 [0.01;0.44]	0.005	0.18 [0.00;0.36]	0.046
Hyperactivity	0.48 [0.22;0.74]	<0.001	0.34 [0.08;0.60]	0.012	0.35 [0.16;0.53]	<0.001	0.25 [0.06;0.43]	0.008
Peer relationship	0.19 [0.02;0.37]	0.032	0.15 [-0.03;0.33]	0.097	0.15 [0.03;0.27]	0.017	0.12 [-0.01;0.02]	0.060
CBCL (z-scores)								
Total	0.81 [0.64;0.98]	<0.001	0.72 [0.55;0.88]	<0.001	0.58 [0.47;0.70]	<0.001	0.52 [0.40;0.63]	<0.001
anxious/depressed	0.79 [0.61;0.97]	<0.001	0.69 [0.52;0.86]	<0.001	0.56 [0.44;0.68]	<0.001	0.50 [0.38;0.61	<0.001
withdrawn	0.51 [0.33;0.69]	<0.001	0.48 [0.29;0.66]	<0.001	0.38 [0.25;0.50]	<0.001	0.35 [0.22;0.48]	<0.001
somatic complaints	0.57 [0.39;0.75]	<0.001	0.44 [0.26;0.61]	<0.001	0.41 [0.29;0.54]	<0.001	0.32 [0.20;0.45]	<0.001
social problems	0.80 [0.62;0.98]	<0.001	0.73 [0.55;0.91]	<0.001	0.57 [0.48;0.70]	<0.001	0.52 [0.40;0.65]	<0.001
thought problems	0.43 [0.37;0.71]	<0.001	0.45 [0.28;0.62]	<0.001	0.39 [0.27;0.50]	<0.001	0.33 [0.21;0.45]	<0.001
attention problems	0.73 [0.56;0.90]	<0.001	0.63 [0.46;0.81]	<0.001	0.52 [0.40;0.64]	<0.001	0.45 [0.33;0.57]	<0.001
rule breaking behavior	0.32 [0.14;0.50]	<0.001	0.27 [0.08;0.45]	0.004	0.24 [0.11;0.36]	<0.001	0.20 [0.07;0.33]	0.002
aggressive behavior	0.58 [0.42;0.76]	<0.001	0.53 [0.36;0.69]	<0.001	0.42 [0.31;0.54]	<0.001	0.38 [0.27;0.50]	<0.001
internalizing	0.80 [0.63;0.97]	<0.001	0.69 [0.52;0.86]	<0.001	0.58 [0.45;0.70]	<0.001	0.50 [0.38;0.62]	<0.001
externalizing	0.56 [0.39;0.73]	<0.001	0.50 [0.33;0.67]	<0.001	0.41 [0.29;0.53]	<0.001	0.37 [0.25;0.48]	<0.001

Note: Lden (00:00–24:00), 5 dB penalty for the evening measurements (18:00–23:00) and 10 dB penalty for the night measurements (23:00–07:00); Lnight (23:00–07:00); SDQ, Strengths and Difficulties Questionnaire; CBCL, Child Behavior Checklist
a ordinal logistic regression for SDQ categories
b linear regression for SDQ raw scores and CBCL z-scores
c adjusted for gender, age, birthweight, small for gestational age, prematurity, APGAR score after 5 min, disabilities, age of mother at birth, caregiver's skin-color, marital status, caregiver's grade, income category, financial support, household size, MICS stimulation score

Table 3
Association between community noise exposure (Lden and Lnight) and cognitive development problems assessed by the PRIDI in 3-year old children (n = 2930) and by IDELA in 6-year old children (n = 1490) using a linear regression analysis.

	Lden				Lnight			
Assessment	Coef. [95% CI] per 10 dB unadjusted	*p*-value	Coef. [95% CI] per 10 dB adjusted[a]	*p*-value	Coef. [95% CI] per 10 dB unadjusted	*p*-value	Coef. [95% CI] per 10 dB adjusted[a]	*p*-value
PRIDI (z-score)								
Total	0.04 [-0.01;0.15]	0.551	0.08 [-0.04;0.19]	0.184	0.02 [-0.01;0.10]	0.607	0.05 [-0.03;0.13]	0.195
IDELA (percent)								
Total	−0.21 [-2.50;2.08]	0.858	−0.49 [-2.71;1.74]	0.668	−0.24 [-1.83;1.35]	0.771	−0.40 [-0.20;0.11]	0.608
Emergent Numeracy	−1.77 [-4.25;0.72]	0.164	−1.55 [-4.05;0.93]	0.221	−1.33 [-3.05;0.39]	0.130	−1.2 [-2.88;0.06]	0.185
Social-Emotional Skills	0.93 [-1.61;3.48]	0.473	0.71 [-1.87;3.28]	0.591	0.70 [-1.06;2.47]	0.433	0.57 [-1.21;2.34]	0.532
Executive functioning	−2.11 [-6.19;1.96]	0.308	−1.77 [-5.90;2.36]	0.401	−1.63 [-4.46;1.19]	0.257	−1.36 [-4.23;1.51]	0.353
Emergent Literacy	0.28 [-2.93;3.49]	0.864	−0.50 [-3.62;2.62]	0.754	0.10 [-2.14;2.33]	0.934	−0.41 [-2.58;1.76]	0.713
Fine Motor Skills	−0.06 [-3.57;3.45	0.975	−0.93 [-4.45;2.58]	0.603	−0.35 [-2.80;2.11]	0.782	−0.94 [-3.40;1.52]	0.455
Gross Motor Skills	3.51 [-0.43;7.47]	0.081	3.70 [-0.30;7.70]	0.070	2.45 [-0.28;5.18]	0.079	0.26 [-0.16;5.40]	0.064

Note: Lden (00:00–24:00), 5 dB penalty for the evening measurements (18:00–23:00) and 10 dB penalty for the night measurements (23:00–07:00); Lnight (23:00–07:00); PRIDI, Project on Child Development Indicators; IDELA, International Development and Early Learning Assessment.
a adjusted for gender, age, birthweight, small for gestational age, prematurity, APGAR score after 5 min, disabilities, age of mother at birth, caregiver's skin-color, marital status, caregiver's grade, income category, financial support, household size, MICS stimulation score.

the exposure–response association for behavioral problems (Table 5) but this was only a relatively small proportion (6% of the 3 year sample and 28% of the 6 year sample). Additionally, we performed sensitivity analyses for children not living in the informal settlement of Paraisópolis which features the highest noise exposure as well as the highest rates of poverty. Mean Lden of children living in Paraisópolis was 78 dB at 3 years of age versus 69 dB for children living outside of Paraisópolis (Lnight 72 dB versus 60 dB. Frequencies of borderline and abnormal SDQ total difficulties scores were 15% and 19% for children living in Paraisópolis and 10% and 13% for children living outside of Paraisópolis. No association was found for community noise exposure and the SDQ categories at 3 years of age in children living outside of Paraisópolis, whereas, a reduced but still significant association was found for community noise exposure and CBCL total problems z-score at 6 years of age (Table 5).

An additional analysis was conducted with adjusting the main analyses for depression and parental stress (parental stress only available for 3-year analysis) since it is unclear whether these variables act as intermediate endpoints or confounders. Resulting exposure-responses were slightly lower compared to the main analyses (Table 5).

5. Discussion

In the present study we investigated the association between community noise exposure at home and cognitive and behavioral development in children in São Paulo between three and six years of age. Our results suggest that noise exposure is not only associated with an increased risk of behavioral problems in cross-sectional analyses, but

Table 4
Longitudinal association between a 10 dB increase in community noise exposure (Lden) and child behavioral and cognitive development.

		Mean change in behavioral difficulty z-score					Mean change in cognitive z-score			
Exposure	n	Coef [95% CI] per 10 dB adjusted[a] Lden 3y[b]	*p*-value	Coef [95% CI] per 10 dB adjusted[a] Lden 6y[c]	*p*-value	n	Coef [95% CI] per 10 dB adjusted[a] Lden 3y[b]	*p*-value	Coef [95% CI] per 10 dB adjusted[a] Lden 6y[c]	*p*-value
Whole sample	1074					948				
Lden		0.62 [0.38;0.87]	<0.001	0.52 [0.28;0.77]	<0.001		-0.27 [-0.55;0.00]	0.054	−0.27 [-0.55;0.00]	0.053
Lnight		0.44 [0.28;0.61]	<0.001	0.36 [0.19;0.53]	<0.001		-0.20 [-0.39;-0.01]	0.045	−0.20 [-0.39;-0.01]	0.044
Not moved[d]	859					757				
Lden				0.54 [0.24;0.84]	<0.001				−0.47 [-0.79;-0.14]	0.005
Lnight				0.38 [0.18;0.59]	<0.001				−0.33 [-0.55;-0.10]	0.004
Moved[e]	215					191				
Lden		0.59 [0.13;1.05]	0.013	0.27 [-0.22;0.76]	0.280		0.26 [-0.29;0.80]	0.352	0.11 [-0.43;0.64]	0.688
Lnight		0.42 [0.11;0.75]	0.009	0.18 [-0.17;0.53]	0.302		0.16 [-0.22;0.54]	0.405	0.07 [-0.40;0.44]	0.706

Note: Table shows estimated mean z-score difference of the SDQ in 3-year old children and the CBCL in 6-year old children for behavior problems in columns 1 and 2. Columns 3 and 4 show estimated mean changes in child cognitive development assessed by the PRIDI in 3-year old children and by the IDELA in 6-year. All models are estimated using linear regression analysis. Lden (00:00–24:00), 5 dB penalty for the evening measurements (18:00–23:00) and 10 dB penalty for the night measurements (23:00–07:00); SDQ, Strengths and Difficulties Questionnaire; CBCL, Child Behavior Checklist; PRIDI, Project on Child Development Indicators; IDELA, International Development and Early Learning Assessment.
[a] adjusted for gender, age, birthweight, small for gestational age, prematurity, APGAR score after 5 min, disabilities, age of mother at birth, caregiver's skin-color, marital status, caregiver's grade, income category, financial support, household size, MICS stimulation score.
[b] Lden at 3-year address, left empty for children who had not moved, because Lden 3y and Lden 6y is identical.
[c] Lden at 6-year address.
[d] restricted to children who had not moved between 3- and 6-year assessment.
[e] restricted to children who moved between 3- and 6-year assessment.

Table 5
Sensitivity analyses for associations between exposure to community noise (Lden and Lnight) and child behavioral development assessed by the SDQ in 3-year old children and by CBCL in 6-year old children.

		Lden				Lnight			
assessment	n	[95% CI] per 10 dB unadjusted	*p*-value	[95% CI] per 10 dB adjusted[c]	*p*-value	[95% CI] per 10 dB unadjusted	*p*-value	[95% CI] per 10 dB adjusted[c]	*p*-value
SDQ total difficulties score	**OR[a] [95% CI]**			**OR[a] [95% CI]**		**OR[a] [95% CI]**		**OR[a] [95% CI]**	
main analysis[d]	3358	1.46 [1.16; 1.83]	0.001	1.32 [1.04;1.68]	0.021	1.32 [1.13;1.55]	0.001	1.24 [1.05;1.46]	0.012
Excluding home moving[e]	3140	1.42 [1.12;1.79]	0.004	1.29 [1.01;1.65]	0.039	1.30 [1.10;1.53]	0.002	1.22 [1.03–1.44]	0.024
Excluding Paraisópolis[f]	2975	1.08 [0.78;1.50]	0.637	0.93 [0.66;1.31]	0.675	1.09 [0.87;1.37]	0.468	0.97 [0.76;1.24]	0.825
Including additional variables[g]	3358			1.24 [0.98;1.57]	0.079		0.468	1.18 [1.00;1.39]	0.050
CBCL total problems score	**Coef.[b] [95% CI]**			**Coef.[b] [95% CI]**		**Coef.[b] [95% CI]**		**Coef.[b] [95% CI]**	
main analysis[d]	1488	0.81 [0.64;0.98]	<0.001	0.72 [0.55;0.88]	<0.001	0.58 [0.47;0.70]	<0.001	0.52 [0.40;0.63]	<0.001
Excluding home moving[e]	1076	0.78 [0.57;0.98]	<0.001	0.71 [0.50;0.91]	<0.001	0.55 [0.41;0.69]	<0.001	0.50 [0.36;0.64]	<0.001
Excluding Paraisópolis[f]	1319	0.46 [0.27;0.66]	<0.001	0.44 [0.24;0.63]	<0.001	0.34 [0.21;0.48]	<0.001	0.32 [0.19;0.46]	<0.001
Including additional variables[h]	1488			0.56 [0.41;0.72]	<0.001			0.41 [0.30;0.51]	<0.001

Note: Lden (00:00–24:00), 5 dB penalty for the evening measurements (18:00–23:00) and 10 dB penalty for the night measurements (23:00–07:00); Lnight (23:00–07:00); SDQ, Strengths and Difficulties Questionnaire; CBCL, Child Behavior Checklist.
[a] ordinal logistic regression for SDQ total difficulties score classification (normal, borderline, abnormal).
[b] linear regression for CBCL total problems score.
[c] adjusted for gender, age, birthweight, small for gestational age, prematurity, APGAR score after 5 min, disabilities, age of mother at birth, caregiver's skin-color, marital status, caregiver's grade, income category, financial support, household size, MICS stimulation score.
[d] including all children of the study population.
[e] restricted children who had not moved in the past 3 years.
[f] excluding children living in the informal settlement of Paraisopolis.
[g] adjusting additionally for depression status and parental stress scores of caregiver.
[h] adjusting additionally for depression status of caregiver.

also predicts an increased longitudinal risk in behavioral difficulties and a decline in cognitive functioning in this age group.

To our knowledge, this is the first longitudinal study to report a positive association between community noise and behavioral difficulties among children in a LMIC. In previous cross-sectional studies focusing on noise exposure at school or at home conducted in Europe, associations were observed for subcategories but not the SDQ total difficulties score (Crombie et al., 2011; Stansfeld et al., 2009; Tiesler et al.,

2013) or no association with behavioral problems at all (Haines et al., 2001b). Hjortebjerg et al., who investigated traffic road exposure at homes of 7-year old children, found an association with the SDQ total difficulties score, as well as hyperactivity subscore, but not for other subscores (Hjortebjerg et al., 2016). Dreger et al. demonstrated associations with the SDQ total difficulties score, emotional problems, conduct problems and peer relationship problems but not with hyperactivity (Dreger et al., 2015). However, this study used parental noise annoyance as a proxy for children's noise exposure and is thus less comparable to our study. Two studies using the CBCL scores did not observe an association between road traffic noise exposure at home and CBCL total problems score (Lim et al., 2018) or road traffic noise exposure at home and school and the CBCL subscale for attention deficit/hyperactivity disorder (ADHD) (Zijlema et al., 2021). However, children included in these studies were significantly older compared to our study population, with 10–12 years of age. In line with previous studies, strongest associations were observed with hyperactivity and inattention (Crombie et al., 2011; Hjortebjerg et al., 2016; Tiesler et al., 2013). One reason why hyperactivity may be significantly associated with noise exposure is that hyperactive children can get more easily distracted by background noise (Gray et al., 2002) which can exacerbate their difficulties leading to a worse or more obvious tendency toward hyperactivity (Stansfeld et al., 2009).

According to our study, 14 % of the children were defined as abnormal based on the SDQ total difficulties score. This might seem quite high. We chose the most commonly used cut-offs for defining an abnormal SDQ score, also proposed by Fleitlich et al. (Fleitlich et al., 2000) for the Brazil population. The same cut-offs were also used in other Brazilian studies (Cury and Golfeto, 2003; Goodman et al., 2012; Hokama dos Santos et al., 2018), where even higher proportions of abnormal scores were found ranging from 37% to 46%.

The association between cognitive development and noise exposure in children has been more intensively studied. In a systematic review of the WHO in 2018, 34 papers linking noise exposure to cognitive development of children were identifed (Clark and Paunovic, 2018a). They found that the quality of the evidence ranges from moderate quality for an effect for some outcome-exposure combinations (e.g., reading and oral comprehension in relation to aircraft noise) to no considerable effect for other outcomes (e.g. attention and executive function or reading comprehension in relation to road traffic noise). However, most of these studies were performed at school and mainly focused on aircraft noise exposure.

Our study differs in several important aspects from the literature described here, which may explain the much clearer signal we see in our data. First, most of the previous studies were substantially smaller than our study, limiting their power to detect the rather small associations. Second, most studies were conducted at schools and not at children's homes, where children may be less affected by noise due to better infrastructure or because community noise may be predominated by children's activities. Most children spend the majority of their time at home, where noise exposure thus can be expected to have an important role as well, where they may be adversely impacted in several activities such as communication, homework, rest and sleep. Noise may be particularly important at night due to sleeping disturbances documented in the literature (Basner and McGuire, 2018; Pirrera et al., 2010; Tiesler et al., 2013), and the importance of sleep quality for children's development (Gregory and Sadeh, 2012; Huhdanpää et al., 2019; Quach et al., 2009). Interestingly, we find stronger associations for Lden than Lnight which is not in line with previous studies (Dreger et al., 2015; Tiesler et al., 2013), although the high correlation between our Lden and Lnight estimates prevents from firm conclusion. Third, the area studied was without any doubt very noisy, with average noise exposures much higher compared to those seen in previous studies. For instance, a recent land use regression noise modelling study conducted in the city of Koblenz (Germany) found for residential areas a mean Lden of 51.4 dB (interquartile range: 46.2–55.3 dB) (Staab et al., 2021). As shown in Fig. 4, we find harmful effects primarily above 70 dB for Lden and 60 dB for Lnight, which were very common in the study area and presumably also in a range of similar urban low- and middle-income settings globally. High noise levels in São Paulo were not only detected by our LUR model but have been previously measured by others (Moura-De-Sousa et al., 2002; Paiva-Vianna and Cardoso, 2016). It should be noted that land use regression noise models capture total community noise and thus reported levels cannot directly be compared with studies restricted to modelled transportation noise.

A fourth explanation for our different results compared to previous studies might be our younger study population of pre-school children. A Massachusetts General Hospital (MGH) study found evidence for the vulnerability of children being age-dependent and showed that children under 3 years old are the most vulnerable to adversity (Gabard-Durnam and McLaughlin, 2019).

Last but not least, a possible reason why we found stronger associations may be our low-income setting. Previous studies demonstrated that children from low-income families have higher average baseline stress levels (Attar et al., 1994; Kryski et al., 2013), which may make children more vulnerable to additional sources of stress. In addition, sound insulation of the buildings is poorer resulting in higher indoor noise levels. Supporting this theory, one study, comparing noise sensitivity between a low- and a high-income country could demonstrate higher values in the low-income country (Sieber et al., 2018). The fact that low-income settings might worsen the effect of noise exposure is supported when looking at our sensitivity analysis demonstrating more pronounced associations in the full sampling including the low socioeconomic area Paraisópolis. Alternatively, the result of this sensitivity analysis may indicate residual confounding by socioeconomic factors. In our study, we have considered many factors related to socioeconomic status, which goes beyond what has been done in previous studies.

A major strength of our study is the access to residential address histories at birth, 3 and 6 years of age and behavioral and cognitive assessments at different follow-up periods, which enabled us to not only perform cross-sectional but also longitudinal analyses. Longitudinal studies are most informative to draw conclusions about causal inference and longitudinal evidence is rare. Clark et al found a weak longitudinal association between aircraft noise and poorer reading but no longitudinal association between aircraft noise and behavior problems (Clark et al., 2013). Weyde et al could show an association between long term residential exposure to road traffic noise and inattention using data from the Norwegian Mother and child cohort (Weyde et al., 2017). It is unknown if prolonged exposure to noise leads to increased, constant or even lessen effects due to adaptation. Haines et al provided evidence that the effect of noise exposure on child cognition do not habituate within one year (Haines et al., 2001c). In a Danish cohort study with 46′940 included children, exposure to road traffic noise during pregnancy was not associated with child behavioral problems at 7 years of age but postnatal exposure was (Hjortebjerg et al., 2016). We observed stronger association in the longitudinal exposure–response analysis of non-movers compared to movers for cognitive functions but not for behavioral problems, which may indicate that cumulative long term noise exposure without adaption is most relevant for cognitive development, whereas for behavioral problems exposure at the age of 3 years seemed to be most crucial.

Further strengths are the large sample size and rich dataset to consider potential confounding.

Some limitations have to be considered. One limitation of this study is attrition in the 6-years follow-up which was affected by the COVID-19 pandemic. However, analyses comparing the baseline characteristics of participants at birth, 3 and 6 years revealed little differences in baseline sociodemographic or exposure variables. Noise measurements for the noise modelling were conducted in 2019 and had to be applied to previous years when children were younger and we could not apply time-varying noise exposure levels. However, in general noise exposure levels are found to be quite stable over time based on the fact of the logarithmic scale and that a doubling of the sound energy results in a 3 dB change only. Correlation of our noise measurements for the LUR model was 0.78 comparing winter and summer season. In a Swiss study, correlation between nationwide road traffic noise modeling in 2001 and 2011 was 0.97. Thus, noise measurements in 2019 likely also represent typical noise exposure when the health data was collected (Karipidis et al., 2014).

Another limitation is the missing information on house type and insulation, whether the apartment of the study child's family is located in an apartment house and whether the child's bedroom faced a busy road or backyard. These factors may influence exposure to noise, which was demonstrated in previous studies for cardiovascular outcomes (Foraster et al., 2014; Selander et al., 2009). Therefore, it is possible that noise levels were over- or underestimated. Additionally, we only had residential addresses of the child. Since almost 5% of the caregivers live separated from their partner and over 30% are single parents, it is possible that the child could be staying part of the time at the partners or grandparents' home, experiencing other noise exposure.

Furthermore, even though we carefully adjusted analyses for variables related to socioeconomic status and other factors which could be associated with noise exposure and child development, we cannot completely eliminate a potential bias. For instance, information on maternal smoking or drinking during pregnancy, which have been both linked to neurodevelopment in childhood (Gaysina et al., 2013; Lund et al., 2020), were not collected in the cohort and could therefore not be examined. However, differences of estimates in adjusted and unadjusted analyses were small and associations statistically highly significant, thus the probability that our findings are explained by factors we were not accounting for is small.

One last point that needs to be mentioned is our limited possibility to consider air pollution in our model since an association between cognitive development and air pollutants is possible (Suades-González et al., 2015). However, results are inconsistent and associations are mainly for older children.

In conclusion, this study is to our knowledge the first to longitudinally study the relationship between community noise exposure and behavioral and cognitive development in children. The results presented indicate that exposure to community noise is not only associated with increased behavior difficulties at both ages 3 and 6, but also predicts increases in behavioral difficulties as well as cognitive declines in this age window. Since children from LMICs and especially from informal settlements may be more vulnerable and more exposed to noise, new strategies to approach the increasing noise problem in rapidly growing urban areas in LMICs are urgently needed.

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Ethical approval

Approval was obtained from the Swiss ethics committee (AO_2020-00025) and Brazilian ethics committee (01604312.1.0000.0065).

CRediT authorship contribution statement

Michelle Raess: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Alexandra Valeria Maria Brentani:** Conceptualization, Data curation, Writing – review & editing. **Benjamin Flückiger:** Methodology, Data curation, Writing – review & editing. **Bartolomeu Ledebur de Antas de Campos:** Data curation, Writing – review & editing. **Günther Fink:** Conceptualization, Funding acquisition, Writing – review & editing. **Martin Röösli:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106961.

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